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RAMJET TECHNOLOGY

Chapter 14

MATERIALS FOR RAMJET ENGINES AND COMPONENTS

by

C.W. BESSERER

The Johns Hopkins University
Applied Physics Laboratory

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(Manuscript submitted for publication
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14. MATERIALS FOR RAMJET ENGINES AND COMPONENTS

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14.1 NATURE OF THE MATERIALS PROBLEM

In few engineering problems are the parameters of any structural design so mutually dependent as in the design of the ramjet engine. The interdependence of load, deflection, temperature, and time creates two new problems, each of which requires a solution before suitable materials can be selected. These problems involve: (a) An evaluation of the mechanical properties of traditional aircraft materials for more severe boundary conditions, and (b) a search for new materials which can be used in areas in which the conventional aircraft materials are inadequate. Both of these problems are unusually troublesome; the first because the basic design problem (with exceptionally varied and numerous parameters) frequently is not fully understood by the designer or materials engineer. An example of this misunderstanding is encountered in the short-time versus long-time temperature problem, which is discussed on page 5. The second problem arises from the fact that materials in the development stage vary in their make-up and have a tendency to be erratic in their mechanical behavior.

An educational problem in fabrication techniques, a careful evaluation of production and fabrication potential, and a re-examination of inspection and testing techniques are also involved in the use of new materials. The problem is exemplified by the development of usable titanium alloys for structural applications. In addition, materials used for guided missiles are subjected to other deleterious environments such as vibration, shock, humidity, sand and dust, salt spray, temperature, pressure, corrosion, fungus, and rain. These conditions are not usually encountered in the same conbination as in more conventional applications.

The specialized requirements for ramjet-engine materials can be discussed more satisfactorily if the engine is considered to be made up of combustion-system components and diffuser-system components. This breakdown by function gives two different temperature zones for design Mach numbers from 1.6 to 2.4. In the first zone, temperature effects are due to hot gases from combustion, and in the second to aerodynamic heating.

The combustion-system components, which for many applications comprise the aft section of the missile, present several of the most complex engineering problems. Suitable metals must be selected which will withstand temperatures varying from 400° to 1800°F. The exact temperature or temperature gradient in any particular component or combustor subsystem obviously depends upon its function, location, and the length of exposure (which may vary from as little as three minutes to as long as three hours).

The tailpipe, which in many cases is also the external skin of the aft body of the missile, may also be the load carrying member. These loads may product various combinations of bending as well as torsional and axial stresses. These

stresses may be steady-state or dynamic, depending on flight conditions, and may correspond to accelerations varying from one g to 30g over a very wide frequency regime. Deflections are associated with load and the manner of load application which, for aerodynamic and operational reasons, must be kept within the elastic range of the material. Since dynamic loads are involved, the problems of resonant-vibration conditions are always present, and frequently a design criterion demands that certain frequencies be avoided to prevent undesirable coupling.

Drag and pressure loads to which the nozzle is subjected result in large tensile stresses. Large thermal stresses may also be present, requiring that space allowances be made for expansion. Deflections of this component, however, are not critical. For long periods of flight, temperatures as high as 1500°F may cause a gradual but continuous erosion of nozzle materials from erosive action of the hot gases.

The combustor, which is perhaps subjected to the highest temperatures in the engine, is exposed to the drag and pressure loads which subject the structural components of the entire system to various combinations of membrane stresses. During a steady-state burning, temperatures from 500° to 1500°F may be encountered in various parts of the combustor. External pressures present a structural stability problem, not amenable to precise analysis, since the components contain a great many discontinuities in the form of holes and louvres.

Combustor accessories such as flameholders require materials having high-temperature strength combined with low erosion properties. A holder must be capable of serving its function without appreciable erosion, since burnout could affect the flame-holding stability, and of secondary importance the metal ions in the exhaust could have an attenuation effect on the guidance-intelligence signals.

In the diffuser system (as in the rest of the missile) load and deflection design criteria are keyed to the function of the component. The design temperatures are a function of Mach number, since components are subjected to aerodynamic heating. For antiaircraft missiles operating up to a Mach number of 2.2, this design temperature is between 350° and 450°F, depending on the type of guidance system used. Higher temperatures may require positive cooling action in this region of the missile, since it houses the electronic equipment and the fuel supply. For antiaircraft missiles operating in the regime of Mach numbers 1.8 to 2.2, it has been common practice for design purposes to use a temperature rate-of-rise of 30 deg/sec, which is considered to be conservative. Because of the low thermal capacity of the thin sheet-metal walls, diffuser materials generally reach equilibrium temperature in a matter of seconds. Frequently the limiting design criterion is stability, since the diffuser wall shell is loaded in bending and torsion. In this case, buckling in torsion or compressive buckling in bending is the measure of this stability.

High strength in a light weight, thin section of given aerodynamic shape is required in the diffuser entry lip. For Mach numbers in excess of 2.2, and for flight times in excess of a few minutes, the problem of erosion becomes overwhelmingly important. In many cases the intake lip must support other pieces of equipment, such as antennas or other intelligence elements, and for such designs there is an added requirement for a high degree of stiffness.

Attachment structures and struts are the remaining diffuser-system components which require a careful selection of materials. A considerable amount of these materials is required because of the nature of these members; hence, the strength-weight ratio is quite important.

Even though the materials used in missile construction will be subjected to high temperatures for only relatively short periods of time, the time-temperature problem is still a very critical one. It is in the time ranges of from a few seconds to as much as five or ten minutes that least is known about the mechanical properties of engineering materials. Because of weight considerations it is desirable to use design allowables as high as possible to take full advantage of thermal delays and the short flight times. The lack of data is partly the result of the newness of the application and partly the result of the current practice of using conservatively extrapolated data for design. It is well known that the physical properties of a material change with temperature, and that mechanical properties that yield point and modulus of elasticity vary downward with an increase of temperature. Design data which allow for creep are available in the literature, and, because this creep problem is solved by tolerating a known amount of plastic deformation over a long period of time (years), the mechanical property data associated with this phenomenon are based on long time periods and plastic deformations. On the other end of the scale, the entire subject of short-time high-temperature behavior of aircraft materials requires, and is receiving, further detailed investigation [3,33]. These investigation programs are usually dissassociated from both the conventional creep problem and the very short-time, high-heating-rate problem typified by rocket-material requirements. As long-range missiles are designed, other temperature-time problems will appear. For example, one such problem which has already become evident is the little understood "creep buckling" which occurs in members loaded in compression with an eccentric load.

Selection of materials for the ramjet engine requires not only the consideration of conventional problems for designing high-speed airframes, but also the problem of storage corrosion and environment. A high degree of reliability combined with a minimum amount of maintenance presents contradictory but necessary design requirements.

14.2 DESIGN CRITERIA

It has been indicated that the "nature of the materials problem" for ramjet engines is very definitely a function of temperature and time in a measure beyond the requirements of more conventional applications. Before proceeding to a discussion of specific types of materials, it would be well to consider in general terms how some of the mechanical properties of materials are affected by temperature and load as a function of time. Time is important as a parameter even though the short flight times for antiaircraft missiles can take advantage of thermal inertias, and therefore utilize higher design allowables than if the material were thoroughly soaked for long periods at the operating temperatures. It can then be shown why certain types of materials are applicable to given components.

Structural materials must have strength and deformation properties adequate for the intended application. Figure 14.2-1 is a comparison of the average yield stresses for a number of structural materials at temperatures up to 2000°F. In general, the lightweight alloys are unfavorable when the temperature exceeds 400°F. In guided-missile structures the strength-weight criterion is important. (For a given geometry and loading condition, the material which gives the lightest member is the best choice.) In high-temperature applications, the strength of a material varies with the temperature, as does the choice of materials based on a strength-weight-temperature criterion. As an example of this, a diffuser wall, subject to bending, torsion and pressure loads, constructed of aluminum alloy, would be lightest up to 500°F; a similar wall of titanium alloy up to 900°F, and a stainless steel wall would be lightest above 900°F (based on yield failure). A comparison of strength-weight-ratio versus temperature for typical materials is shown in Fig. 14.2.2.

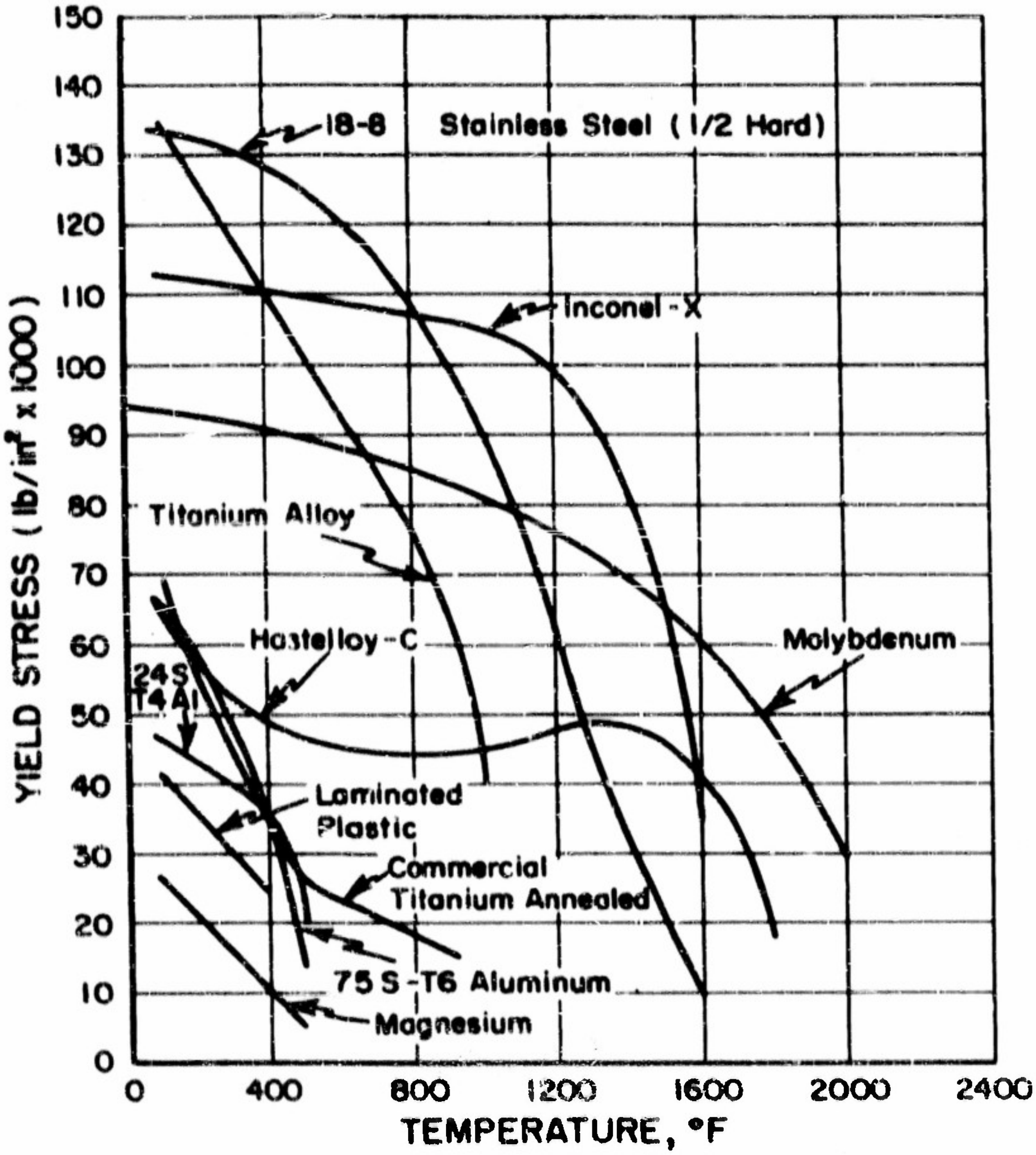


Fig. 14.2-1 YIELD STRESS vs TEMPERATURE

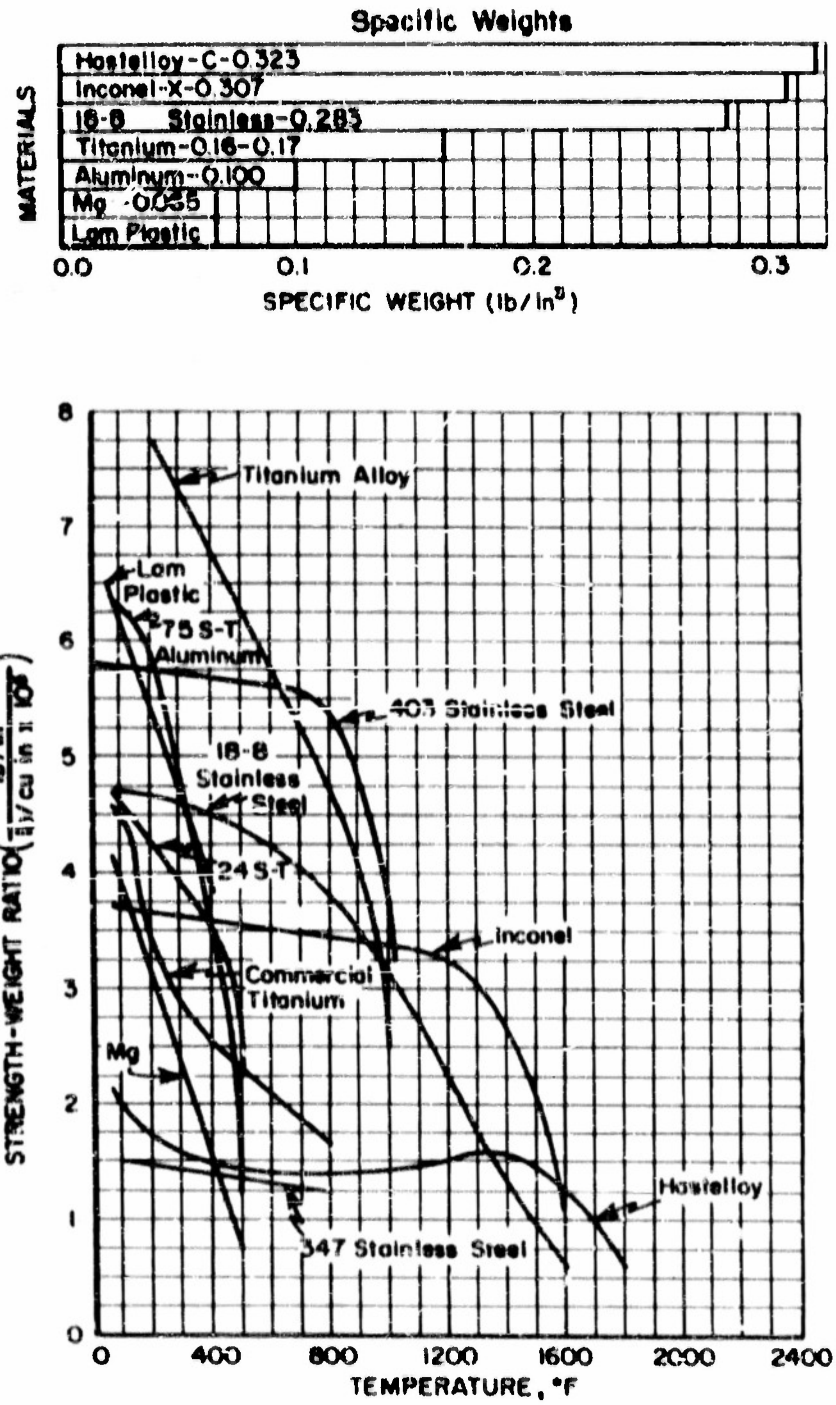


Fig. 14.2-2 TEMPERATURE vs RATIO OF YIELD STRENGTH TO SPECIFIC WEIGHT

After the design environment has been carefully established, full advantage of special properties of certain materials can be realized. In particular, the cost of raw materials may be an important consideration. Figure 14.2-3 shows a comparison of strength-cost ratios versus temperature. It is important to note that this figure does not include consideration of fabrication and possible special tooling costs.

Since the structural material will be subjected to both static and dynamic loads, the strength criterion must be based on the same environment. Hence, the endurance limit of the material will be the appropriate measure of strength. The endurance limit is an indication of the metal's resistance to fatigue phenomenon, which for most engineering metals lies between 1/4 and 1/2 of the ultimate tensile strength of the material for ten million or more repetitions of the load. For the ferrous metals, the endurance limit is considered to approach a limit termed the fatigue strength, which is independent of the number of stress repetitions. This limit disappears at elevated temperature where, for all materials, the endurance limit is a function of the number of applications of the load. The measure of a material's resistance to static elastic deformation is the modulus of elasticity. This relationship, which approximates the ratio of stress to strain in the elastic range as a straight line, is also a function of temperature and decreases in value with an increase in temperature as shown in Fig. 14.2-4. For dynamic deformations, in addition to the modulus of elasticity, the density of the material must be considered, since accelerated masses give inertia forces. An ideal material for dynamic applications might be one as light as magnesium and as stiff as tungsten, but the selection of a material for a particular use is usually based on static rather than dynamic deformations as a structural design criterion.

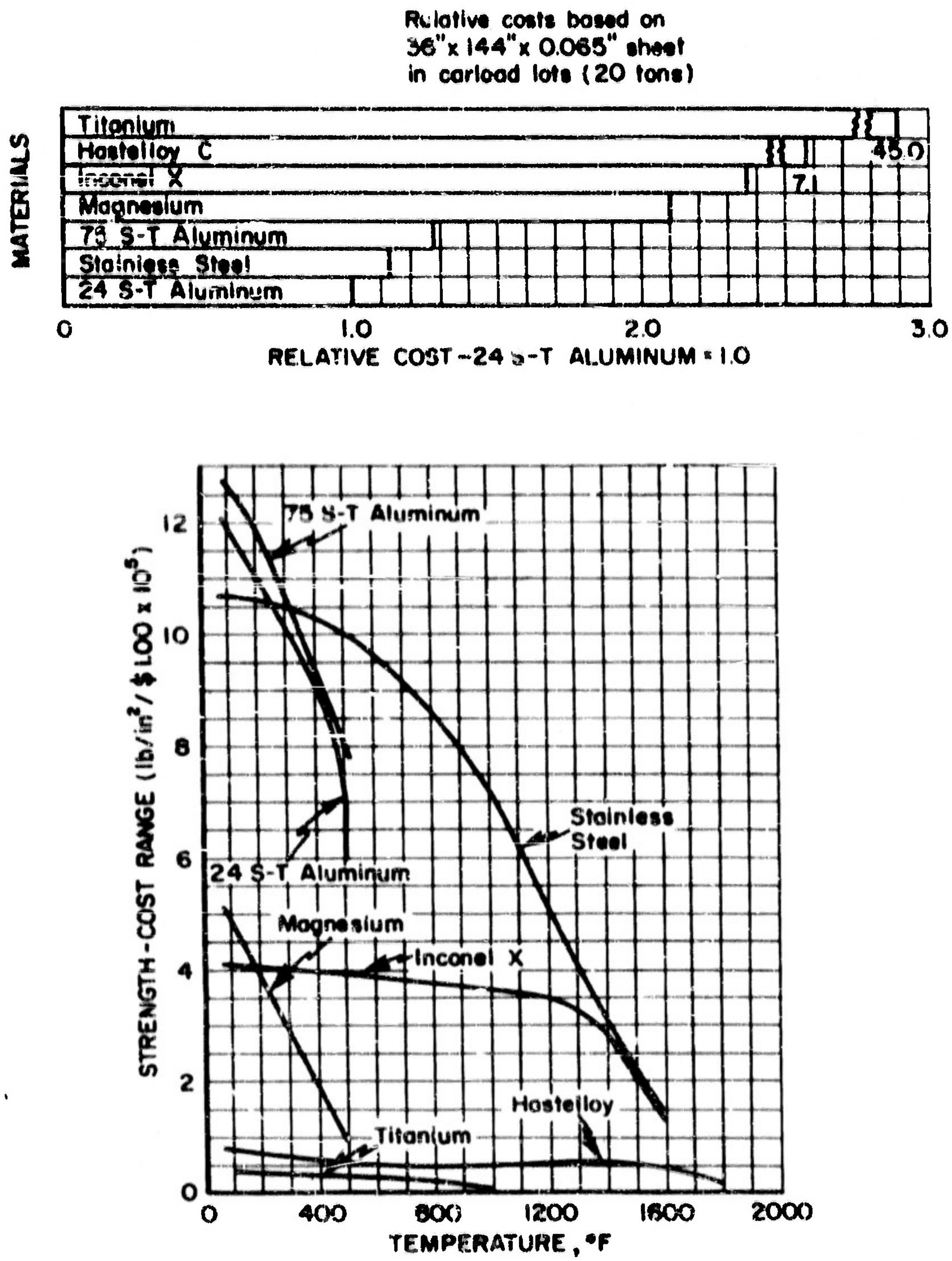


Fig. 14.2-3 TEMPERATURE vs RATIO OF STRENGTH TO COST

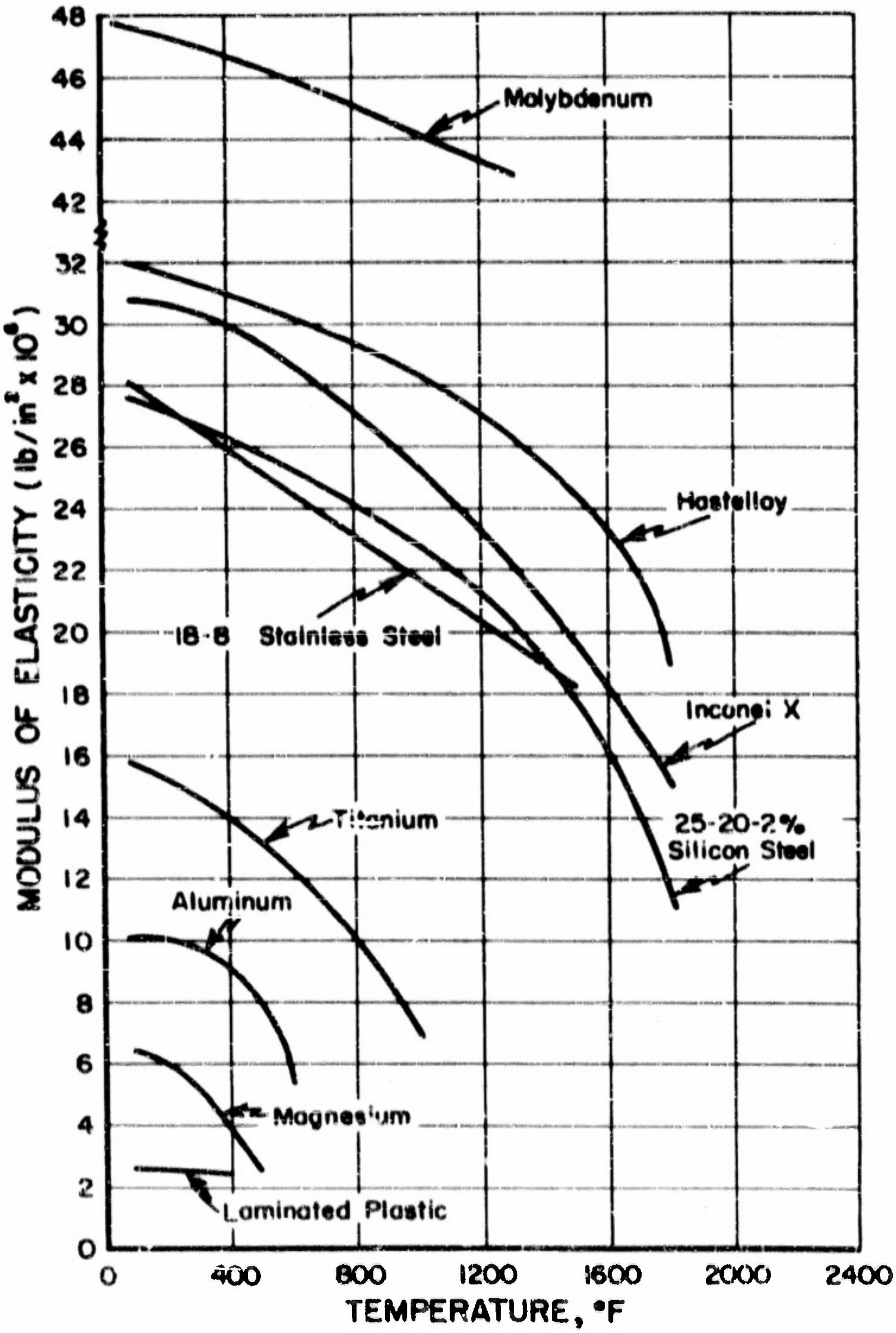


Fig. 14.2-4 MODULUS OF ELASTICITY vs TEMPERATURE

Other mechanical and physical properties such as thermal expansion (Fig. 14.2-5), thermal conductivity (Fig. 14.2-6), and erosion resistance are also important in the selection of materials for ramjet engines and further, these properties increase in importance as missile flight times become longer. The problems of thermal expansion and thermal shock are especially important in built-up structures, particularly those involving several different materials. Consideration of corrosion problems in military applications requires careful selection of adjacent materials unless extraordinary protection precautions are taken. It is preferable to use materials as close to each other as possible in the galvanic series (Table 14.2-1), and in no case separated by more than one grouping.

Another mechanical property of considerable interest is ductility. Since the nature of missile structures leads to combined stresses and stress concentrations, materials with low notch sensitivities are desirable. A usable, but not complete measure of this property is ductility, which shows up in the mechanical properties most commonly as per cent elongation in a specified gage length, and less commonly, but more accurately as per cent reduction of test specimen area. These properties are also some measure of a material's "toughness" which indicate its ability to absorb energy before fracture and is therefore an important measure of workability. For purposes of comparison, Fig. 14.2-7 shows the relative ductility of several typical materials at room temperature. At elevated temperatures the ductility is invariably improved.

Detail design consideration must involve not only the initial temperature, but the actual temperature regime as a function of Mach number, altitude, and temperature history.

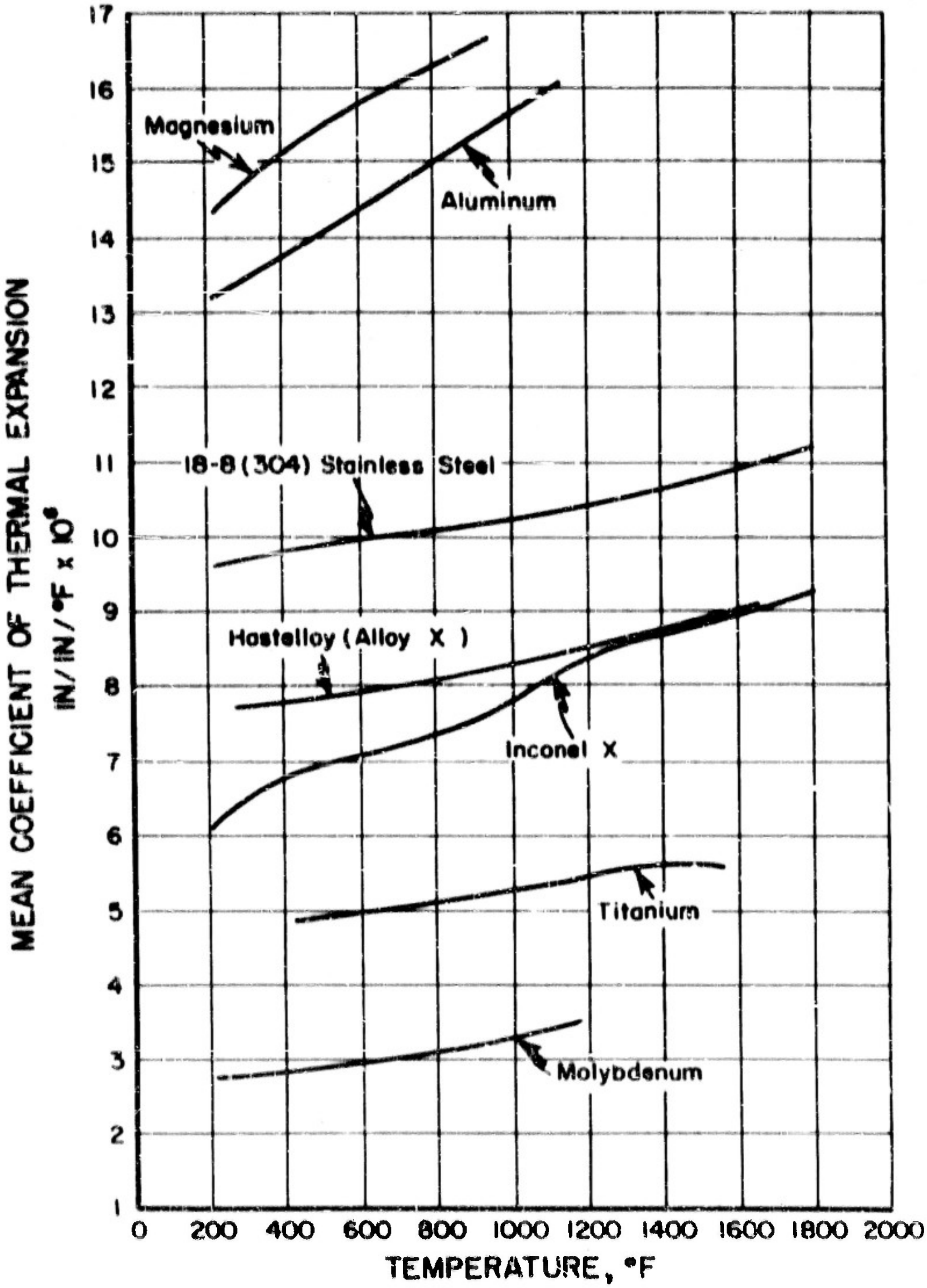


Fig. 14.2-5 THERMAL EXPANSION vs TEMPERATURE FOR SEVERAL MATERIALS

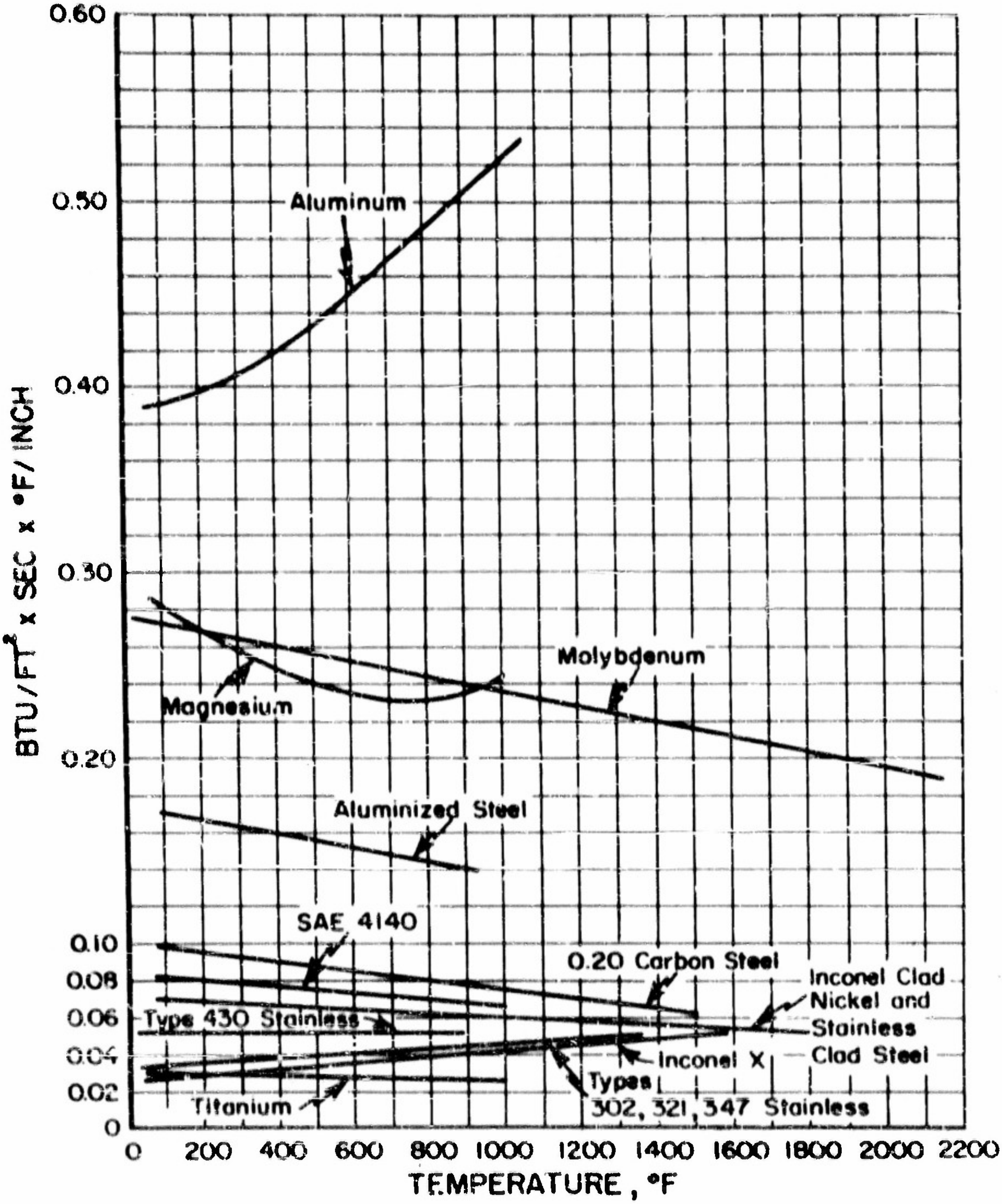


Fig. 14.2-6 THERMAL CONDUCTIVITY vs TEMPERATURE FOR SEVERAL MATERIALS

TABLE 14.2-1 Galvanic Series in Sea Water

Corroded End (anodic, or least noble)

Magnesium

Magnesium Alloys

Zinc

Galvanized Steel or
Galvanized Wrought Iron

Aluminum

(52SH, 4S, 3S, 2S, 61S-T, 53S-T in this order)

Alclad

Cadmium

Aluminum

(A17S-T, 17S-T, 24S-T in this order)

Mild Steel

Wrought Iron

Cast Iron

Ni-Resist

13 per cent Chromium Stainless Steel Type 410 (active)

17 per cent Chromium Stainless Steel Type 430 (active)

Hastelloy C

50-50 Lead Tin Solder

18-8 Stainless Steel Type 304 (active)

18-12-3 Stainless Steel Type 316 (active)

Lead

Tin

Muntz Metal

Manganese Bronze

Naval Brass

Molybdenum

Nickel (active)

Inconel (active)

Hastelloy A

Hastelloy B

Yellow Brass

Admiralty Brass

Aluminum Bronze

Red Brass

Copper

Silicon Bronze

90-10 Copper Nickel

70-30 Copper Nickel

Composite G-Bronze

Composite M-Bronze

Nickel (passive)

Inconel (passive)

Monel

13 per cent Chromium Stainless Steel Type 410 (passive)

17 per cent Chromium Stainless Steel Type 430 (passive)

18-8 Stainless Steel Type 304 (passive)

18-8-3 Stainless Steel Type 316 (passive)

Titanium

Protected End (cathodic, or most noble)

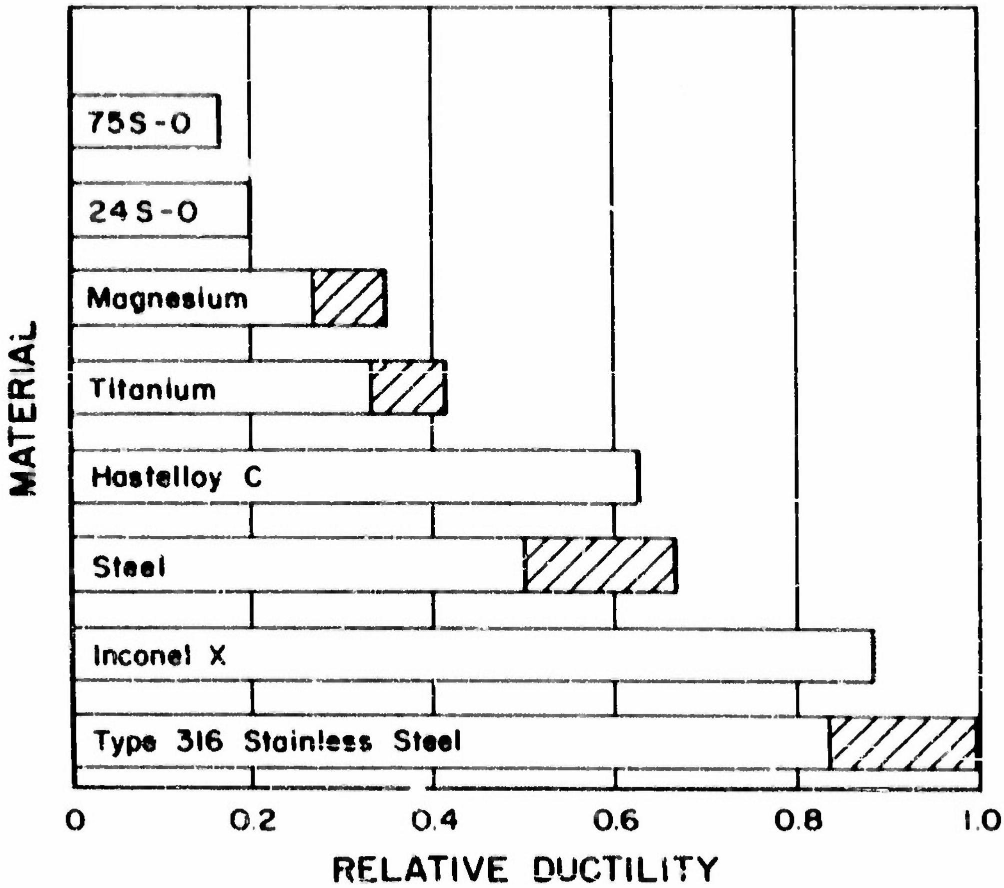


Fig. 14.2-7 RELATIVE DUCTILITIES FOR ANNEALED SHEET MATERIALS AT ROOM TEMPERATURE

Use is made of several different "standard" days (Table 14.2-2) to obtain a starting point for establishing the temperature conditions for correcting the design allowables. Usually for structural design, the "standard" hot and cold days are used, since they represent an envelope of "worst design" conditions. Such standard days cannot exist meteorologically, but conditions at various places on and above the earth can and do match points on the standard day curves; consequently, it is desirable to use these for design. For calculating the performance of a missile, however, it is preferable to use polar and tropical days since these can exist meteorologically.

Any material has certain advantages and disadvantages in a given situation; however, the material selected will usually be a compromise based on the following:

1. It is satisfactory for statical loads,
2. it is satisfactory for dynamical loads,
3. it fulfills special requirements (such as corrosion resistance, damping capacity, etc.)
4. it is practical to fabricate on a production basis,
5. it is available (and is not a critical material in time of war).

A means of rating strategic and critical materials [1] is frequently of value in performing both preliminary and production design. In determining which one of several suitable materials should be selected for a specific application, consideration should be given to the current and possible future scarcity of the material.

This is a method of rating an element numerically according to its relative scarcity by applying material factors ("MF") to the element. Boron, which is considered abundant and noncritical, is given an "MF" of 1, while columbium, considered the most scarce and critical, is given an "MF" of 2200 (Table 14.2-3).

TABLE 14.2-2 Mach Number for Several Standard Days vs Altitude and Velocity

Velocity (ft/sec)		Altitude (feet) Sea Level	10,000	20,000	30,000	40,000	50,000	60,000
1800	Standard (NACA)	1.51	1.67	1.73	1.81	1.85	1.85	1.85
	Hot*	1.55	1.60	1.66	1.73	1.79	1.79	1.79
	Cold*	1.75	1.75	1.83	1.90	1.95	2.00	2.02
	Polar*	1.64	1.70	1.77	1.82	1.82	1.82	1.82
	Tropical*	1.56	1.62	1.68	1.75	1.83	1.91	1.94
1900	Standard (NACA)	1.70	1.76	1.83	1.91	1.95	1.95	1.95
	Hot*	1.64	1.69	1.75	1.82	1.89	1.89	1.89
	Cold*	1.85	1.85	1.93	2.00	2.05	2.11	2.13
	Polar*	1.73	1.80	1.87	1.92	1.92	1.92	1.92
	Tropical*	1.65	1.71	1.77	1.85	1.93	2.01	2.05
2000	Standard (NACA)	1.79	1.86	1.93	2.01	2.06	2.06	2.06
	Hot*	1.72	1.78	1.85	1.92	1.99	1.99	1.99
	Cold*	1.95	1.95	2.03	2.11	2.16	2.22	2.25
	Polar*	1.82	1.89	1.97	2.02	2.02	2.02	2.02
	Tropical*	1.74	1.80	1.87	1.94	2.03	2.12	2.16
2100	Standard (NACA)	1.88	1.95	2.02	2.11	2.16	2.16	2.16
	Hot*	1.81	1.87	1.94	2.02	2.09	2.09	2.09
	Cold*	2.05	2.05	2.14	2.21	2.27	2.33	2.36
	Polar*	1.92	1.99	2.07	2.12	2.12	2.12	2.12
	Tropical*	1.83	1.89	1.96	2.04	2.13	2.23	2.27
2200	Standard (NACA)	1.97	2.04	2.12	2.21	2.26	2.26	2.26
	Hot*	1.90	1.96	2.03	2.11	2.19	2.19	2.19
	Cold*	2.14	2.14	2.24	2.32	2.38	2.44	2.47
	Polar*	2.01	2.08	2.17	2.22	2.22	2.22	2.22
	Tropical*	1.91	1.98	2.05	2.14	2.23	2.33	2.38
2300	Standard (NACA)	2.06	2.14	2.22	2.31	2.37	2.37	2.37
	Hot*	1.98	2.05	2.12	2.21	2.29	2.29	2.29
	Cold*	2.24	2.24	2.34	2.42	2.49	2.55	2.58
	Polar*	2.10	2.18	2.27	2.32	2.32	2.32	2.32
	Tropical*	2.00	2.07	2.15	2.24	2.33	2.44	2.48
2400	Standard (NACA)	2.15	2.23	2.31	2.41	2.47	2.47	2.47
	Hot*	2.07	2.14	2.22	2.30	2.39	2.39	2.39
	Cold*	2.34	2.34	2.44	2.53	2.59	2.66	2.70
	Polar*	2.19	2.27	2.36	2.42	2.42	2.42	2.42
	Tropical*	2.09	2.16	2.24	2.33	2.43	2.54	2.59
2500	Standard (NACA)	2.24	2.32	2.41	2.51	2.57	2.57	2.57
	Hot*	2.16	2.23	2.31	2.40	2.49	2.49	2.49
	Cold*	2.44	2.44	2.54	2.63	2.70	2.78	2.81
	Polar*	2.28	2.36	2.46	2.52	2.52	2.52	2.52
	Tropical*	2.17	2.25	2.33	2.43	2.54	2.65	2.70

*Indicates Proposed Standard Days (see Navy BuAer Powerplants Manual No. 28).

TABLE 14.2-3

Examples of Material Factors

		Current Revised Draft			Current Revised Draft
Aluminum	(Al)	14	Manganese	(Mn)	6
Antimony	(Sb)	5	Molybdenum	(Mo)	28
Beryllium	(Be)	220	Nickel	(Ni)	22
Boron	(B)	1	Selenium	(Se)	50
Cadmium	(Cd)	4	Silicon	(Si)	5
Cerium	(Ce)	24	Silver	(Ag)	2
Chromium	(Cr)	5	Tantalum	(Ta)	800
Cobalt	(Co)	160	Tellurium	(Te)	6
Columbium	(Cb)	2200	Tin	(Sn)	16
Copper	(Cu)	8	Titanium	(ferro)	2
Germanium	(Ge)	4	Titanium	(Ti)	70
Indium	(In)	80	Tungsten	(W)	70
Iron	(Fe)	2	Vanadium	(V)	5
Lead	(Pb)	7	Zinc	(Zn)	6
Lithium	(Li)	80	Zirconium	(Zr)	3
Magnesium	(Mg)	10			

Synthetics

Acrylic resins (lucite, plexiglass)	2
Asbestos, long fiber	3
Cellulose acetate butyrate resin (tenite)	2
Cellulose acetate (plastacele, fibestose, etc.)	1
Glass cloth and glass mat (fiberglas)	2
Melamine-formaldehyde resins (melmac, plaskon, etc.)	2
Phenolic resins (bakelite, durez, etc.)	3
Polystyrene resins (styron, bakelite, etc.)	2
Polyamides (nylon)	3
Polytetrafluoroethylene resin (teflon)	3

Using these material factors, material numbers ("MN") may be obtained for complex materials such as 24S aluminum alloy and 4130 steel. Of several complex materials suitable for a certain application, the one with the lowest "MN" should be chosen if scarcity must be considered.

An example of the method used in determining the "MN" of a complex material, may be illustrated by 4130 steel.

TABLE 14.2-4

Elements A.I.S.I. 4130 Steel	Per Cent by Weight x "MF"
C	0.3 x 0 = 0
Mn	0.5 x 6 = 3.0
Si	0.3 x 5 = 1.5
Cr	1.0 x 5 = 5.0
Mo	0.2 x 28 = 5.6
Fe	97.7 x 2 = 195.4

Total 210.5 carried to nearest whole number = 211 = "MN" for 4130 steel

A tabulation of material numbers for materials of interest to missile designers is found in Table 14.2-5. This list may be kept up to date by reviewing the quarterly or semi-annual changes made in material factors by the Research and Development Board.

TABLE 14.2-5

Material Numbers for Several Complex Materials

Aluminum Alloy	"MN"
14S	1342
17S	1348
24S	1351
52S	1388
61S	1373
75S	1316
356	1324

Aircraft Quality Steels No. (AISI unless otherwise specified)		"MN"
	1095	201
	4130	213
	4340	252
AMS	5350	294
SAF	135 (nitralloy)	234

Stainless Steel

Type	
302	463
303	463
321	517
414	288
Hastelloy X	1400

Brass

Naval brass	728
Commercial brass	730

14.3 APPLICABLE MATERIALS

In this section are covered some of the advantages and disadvantages of present and future ramjet-engine materials. Little will be included of the designer's problem of replacing conventional, production-tried materials with new materials which require different fabrication and tooling techniques and additional training. This educational problem might well be encountered at all technical and subtechnical levels in any stage of material application.

In considering materials for ramjet engines, it will again be convenient to divide the engine into a combustor system and a diffuser system, both of which are combinations of engine and airframe parts.

Materials for the combustor must, for the most part, retain their elastic-range mechanical properties at high temperatures. For design purposes the definition of a high temperature structure is 1500°F, but future requirements may be as high as 3000°F. Austenitic stainless steels of the AISI 302 and 321 types are frequently used for structures at these temperatures. These are low carbon steels with 18 per cent chrome and 8 per cent nickel and are ductile and suitable for the forming and welding techniques common to combustor components. At present no ferritic low alloy steel (which would be more workable, weldable, economical, and less critical) has been developed which can be used at 1500°F. The turbine industry, however, has succeeded in developing a chrome-molybdenum-vanadium ferritic steel good at 1000°F for high pressure turbine applications, indicating that progress is being made in this field. Also available are nonferrous alloys for high temperature service which are superior to stainless steel in their high temperature properties but are more difficult to fabricate, more costly, and

use more critical constituents. Two examples are Hastelloy X, a newly developed nickel-molybdenum alloy (low in strategic alloy content), and Inconel X, a chrome-nickel alloy. If combustor-wall temperatures are increased to 1800°F or above, it becomes necessary to turn to a pure metal like molybdenum, which is at present expensive and difficult to fabricate, or to one of the iron-chromium-nickel-cobalt alloys, such as Haynes alloy No. 25, which have the double disadvantage of being both expensive and composed of critical materials. A large amount of the current material research is being devoted to developing new high-temperature metallic alloys.

At temperatures above 1800°F such nonmetallic materials as technical ceramics may be considered. Special properties of several typical technical ceramics are given in Table 14.3-1. These materials have desirable high-temperature characteristics, but are usually brittle and suitable, almost without exception only for compressive stress loadings. Ceramic coatings are advantageous because they permit the use of less critical materials and may be used if the extra cost of processing and handling is not excessive. Substitution of light alloys for steels by using coatings is usually not feasible in combustor parts, since the working temperature exceeds the usual allowable values very rapidly. The ceramic merely flattens the rate of the temperature-rise curve, but does not act as a complete insulator. Metal-ceramic compositions combining the desirable mechanical properties of both materials may be useful for certain applications, but fabrication is limited to powder metallurgical processes because of the high melting temperatures. Some of these materials are extremely brittle, and cannot be used except under compressive loads. Special design techniques are thus required, and machining is usually done in the unsintered condition.

TABLE 14.3-1 Mechanical Properties of Typical Technical Ceramics

Annealing Temperature (°F)	Yield Point (lb/in^2)	Tensile Strength (lb/in^2)	Elongation (per cent)
(arc-cast, cold rolled from 0.052 to 0.020 inch)			
Longitudinal			
Cold Rolled	151,800	154,300	5
1600	126,500	131,500	12
1700	121,500	124,500	10
1800	111,000	117,300	13
1900	98,000	105,500	17
2000	74,400	88,800	29
2100	73,100	91,300	28
2200	75,500	90,600	26
2300	81,800	88,400	26
2400	75,400	78,800	39
Transverse			
1600	130,200	132,100	3
1700	120,900	120,900	2
1800	--	123,400	2
1900	113,700	114,700	8
2000	81,200	93,500	27
2100	86,700	91,500	16
2200	82,800	91,100	17
2300	55,000	89,400	16
2400	76,800	83,200	22

Tested in 1-inch gauge length, 1/2-inch wide.

Another possible solution to the extreme high-temperature problem in the combustor may lie in the application of protective coatings of existing high-temperature materials.

Diffuser-system components are at present subjected to maximum temperatures of about 450°F. Steel need not be considered until an operating temperature of about 900°F is reached, since competition with the lighter materials would require gauges impractical to fabricate for the required configurations. Light alloys are presently used for diffuser components. Typical design data are shown in Figs. 14.2-1, 14.3-1, 14.3-2, 14.3-3, and 14.3-4. Although the heating rates used to obtain data for Figs. 14.3-2 and 14.3-3 are higher than anticipated for antiaircraft missile structures (except the combustor), the data are consistent and adequate for design. Much more detail is given by the Munitions Board Aircraft Committee [73] from which these data were extracted. New aluminum alloys, at present in the development stage, offer the possibility of about 35 per cent higher strength properties at 600°F than alloys presently in use. A serious shortcoming of aluminum has been the poor weldability of some of its stronger alloys. Magnesium is another material which has strength-weight properties attractive to the designer. Typical design data for some of the alloys are shown in Figs. 14.3-5 and 14.3-6. Magnesium has notch sensitivity as good as aluminum and somewhat better fatigue properties. Recent advances in the field of magnesium-rare earth-zirconium alloys offer good high-temperature properties up to 600°F. Magnesium requires extra precautions to insure corrosion resistance.

In the temperature range between 500° and 900°F, titanium has the mechanical properties, strength, stiffness, and corrosion resistance, required for a good diffuser material. The mechanical

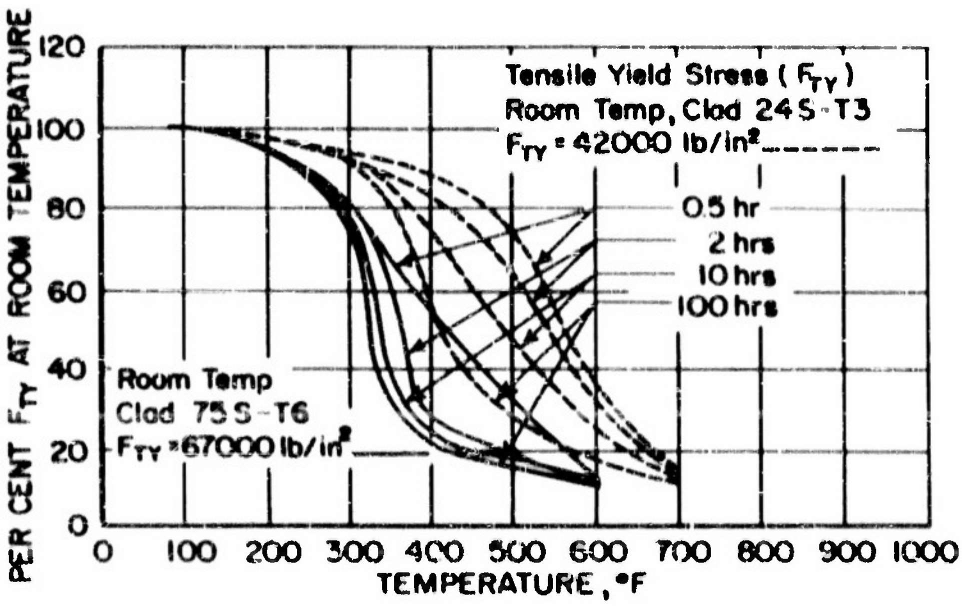


Fig. 14.3-1 EFFECT OF ELEVATED TEMPERATURES ON THE MECHANICAL PROPERTIES OF ALUMINUM ALLOYS 24S-T3 AND 75S-T6

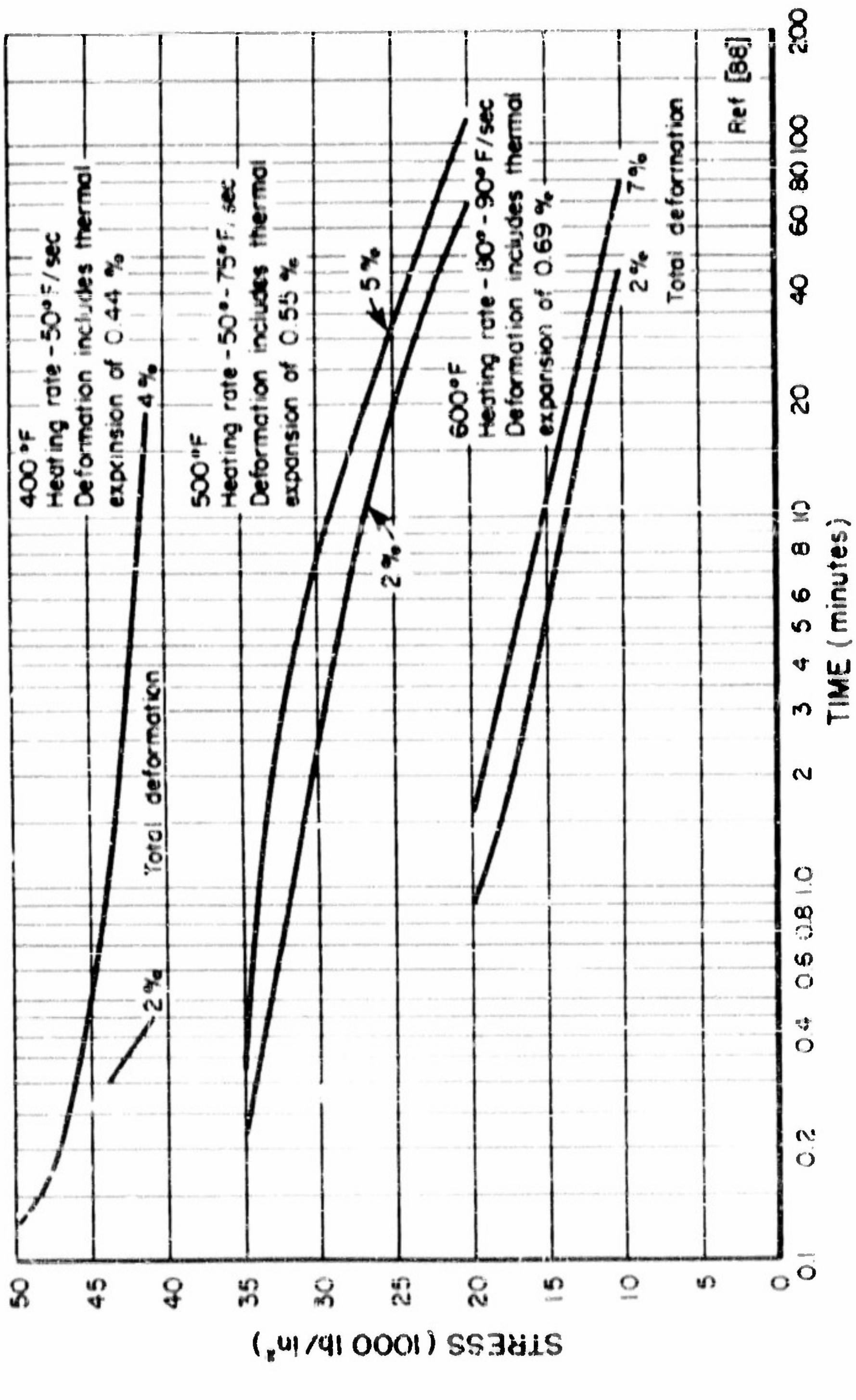


Fig. 14.3-2 DESIGN CURVES FOR 24S-T3 ALUMINUM ALLOY SHEET AT 400°, 500°, AND 600°F

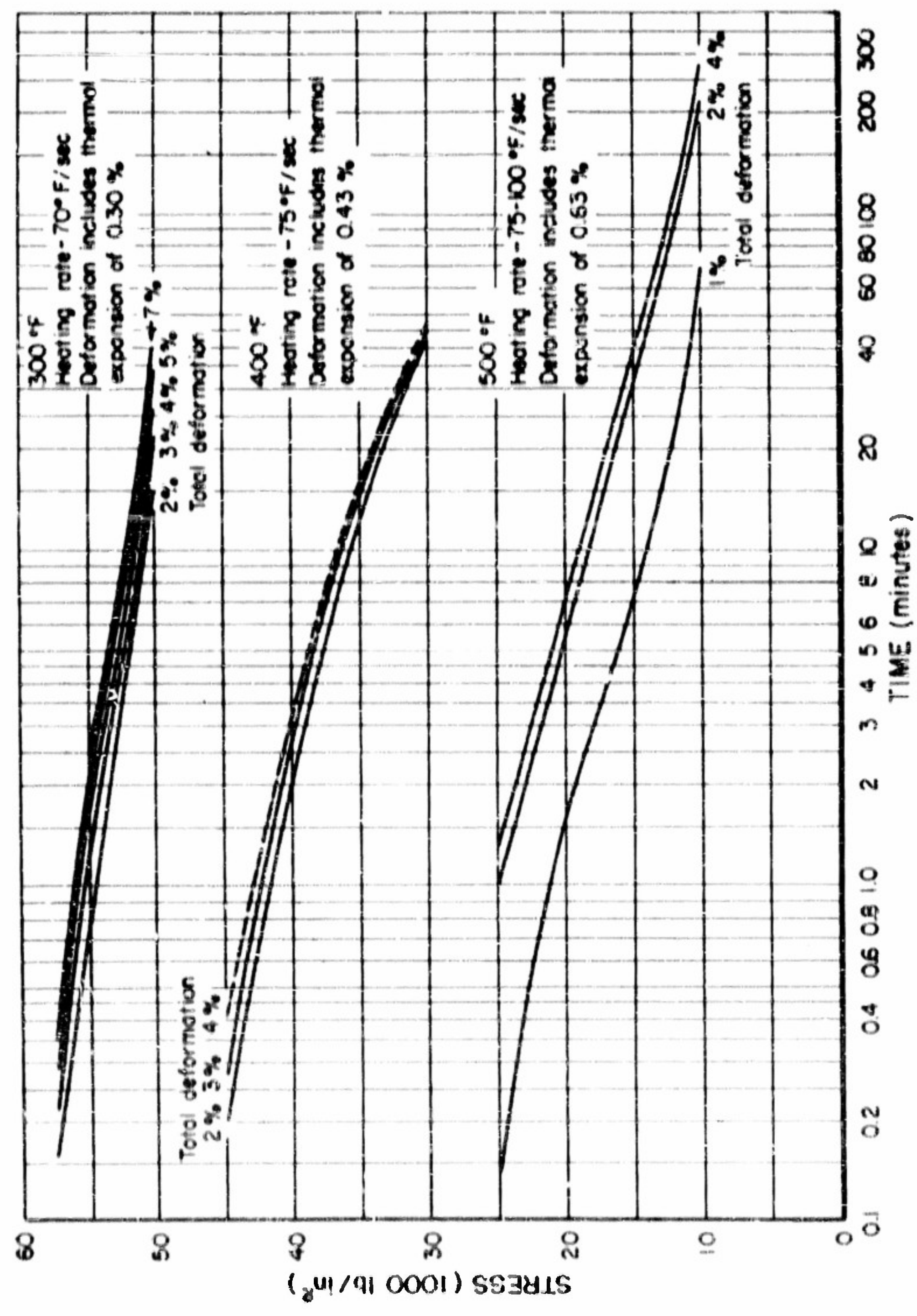


Fig. 14.3-3 DESIGN CURVES FOR 75S-T6 ALUMINUM ALLOY SHEET AT 300°, 400°, AND 500°F

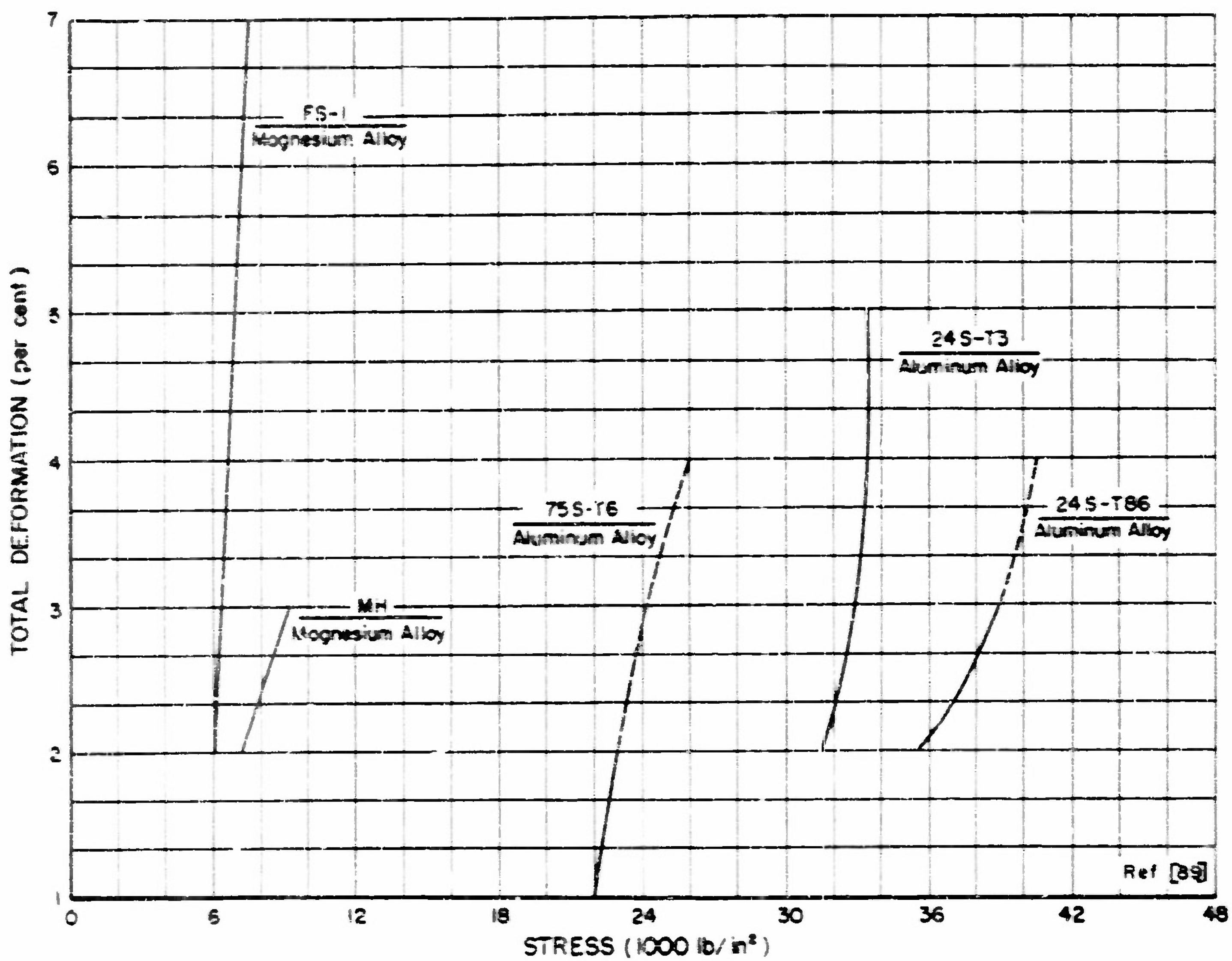


Fig. 14.3-4 STRESS vs TOTAL DEFORMATION CURVES FOR MAGNESIUM AND ALUMINUM BASE ALLOY SHEET UNDER LOAD FOR ONE MINUTE AT 500°F

This curve shows the total deformation produced by stresses acting for one minute. The highest points on each curve, if less than 7 per cent, generally indicate the limit of deformation before rupture.

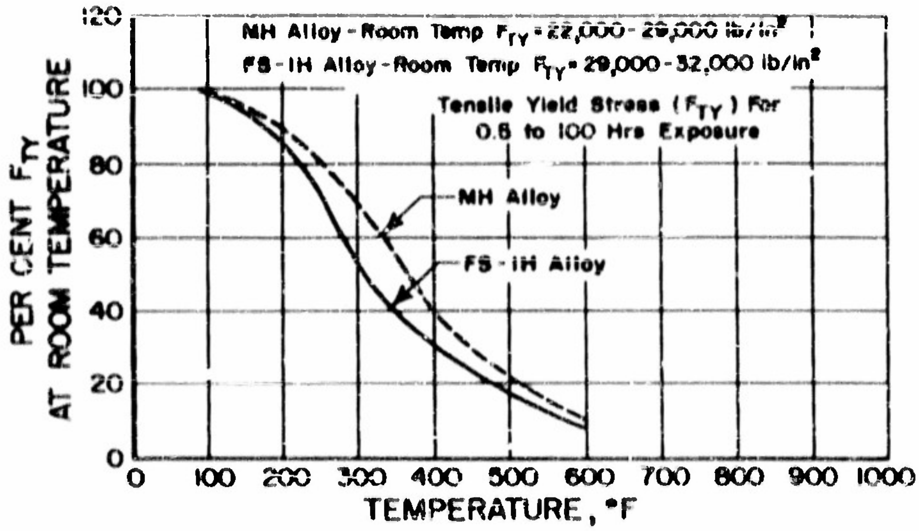


Fig. 14.3-5 EFFECT OF ELEVATED TEMPERATURES ON THE MECHANICAL PROPERTIES OF TWO MAGNESIUM ALLOYS

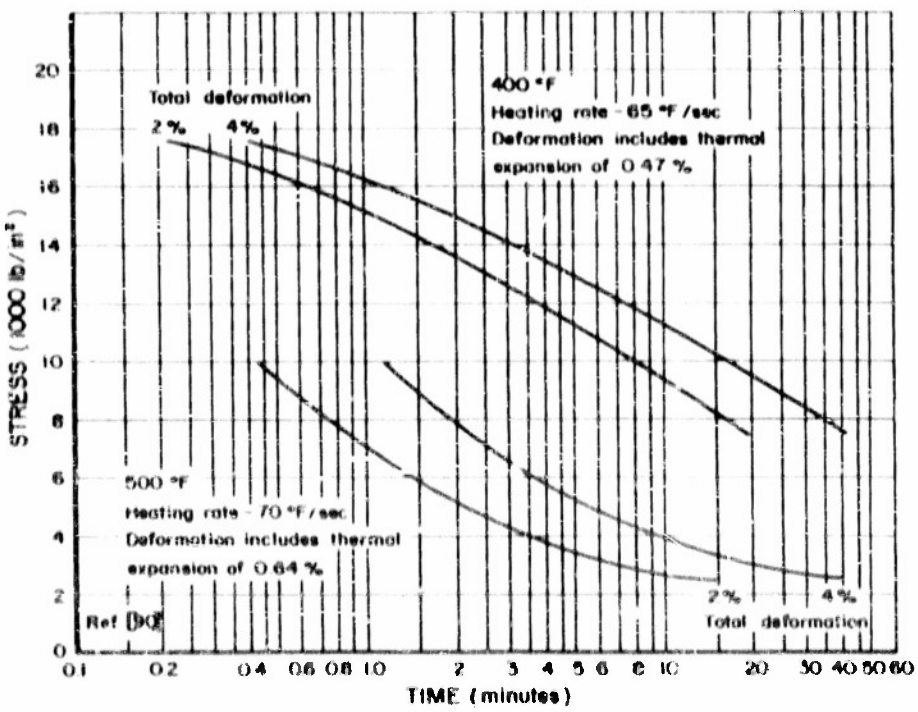
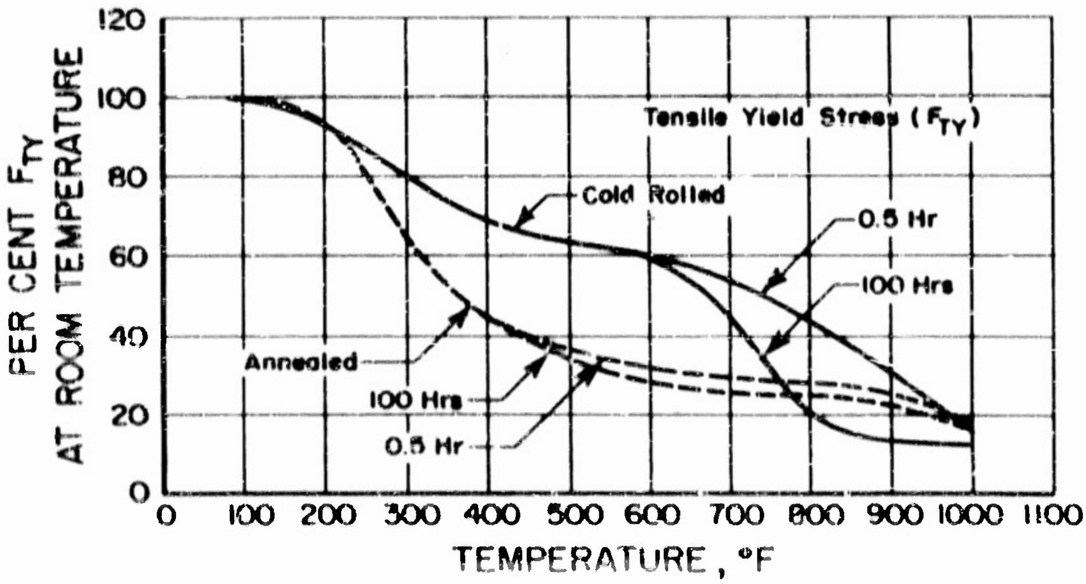


Fig. 14.3-6 DESIGN CURVES FOR MAGNESIUM ALLOY MH AT 400° AND 500°F

properties of titanium and its alloys are not as well established as those for the more conventional materials, but continued use and tests have disclosed weaknesses which will eventually be corrected. Typical design data are given in Fig. 14.3-7 and additional detail information on titanium is given on page

A structural efficiency evaluation [35] of commercial titanium sheet and extruded 75S-T6 and 24S-T3 aluminum alloys with short-time loading indicated that titanium sheet is the more efficient at temperatures above 400°F. The evaluation is given for compressive loading without buckling, for column buckling, and for buckling of long plates in compression or shear. The evaluation extended from 80° to 600°F and also included magnesium ZK60A alloy and 18-8 stainless steel. The stress-strain tests were performed after the material was exposed to the test temperature for one hour, with loading at a strain rate of 0.002 in/in/min. For shorter times, and for titanium alloys other than the commercial grade, it appears that, for temperatures less than 400°F, the advantage also favors the titanium for the cases where allowable stress and not modulus is the determining factor.

Plastics offer another possible structural material for diffuser components. These plastics are used in the form of laminates in which many layers of fabric such as fiberglas are bonded together with a high-temperature resin to form structural sheets of desired thickness with strength properties made to order. Presently available are glass-phenolic laminates capable of use on a favorable strength-weight basis at temperatures up to 500°F. These sheets are amenable to being formed and joined into complex structural members, but they may also be used as the skins of sandwich members with a lightweight metal or plastic core. Typical design data are given



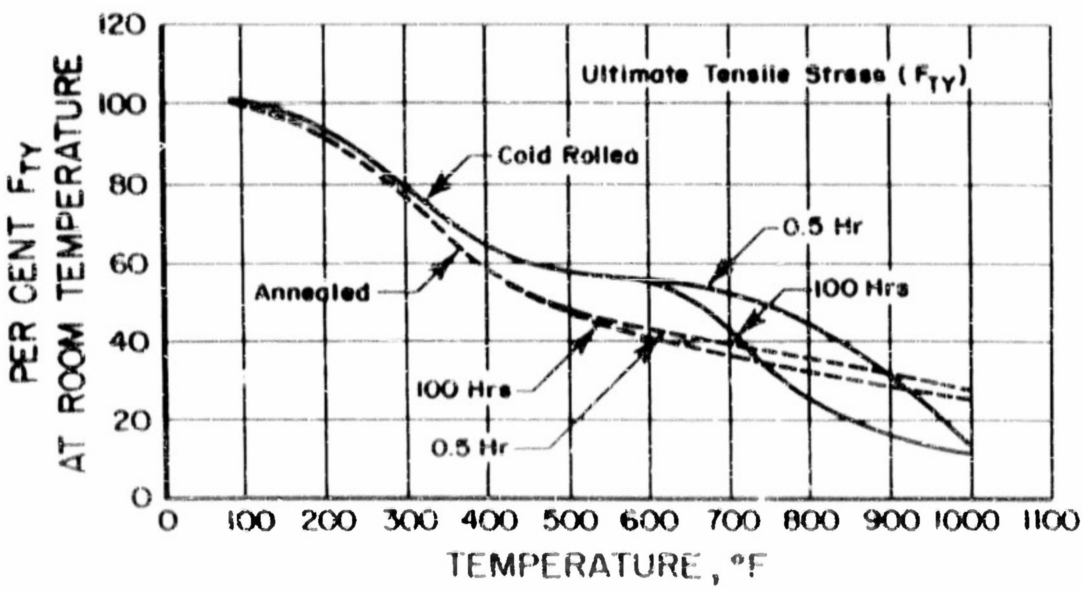


Fig. 14.3-7 EFFECT OF ELEVATED TEMPERATURES ON THE MECHANICAL PROPERTIES OF ANNEALED AND COLD ROLLED TITANIUM

in Fig. 14.3-8. Although it is apparent that design allowables diminish rapidly with increase in temperature, the short flight times and high thermal inertia permit their use extensively, even for primary structures. One of the basic limitations for parts exposed to airflow is the readiness with which some of these materials tend to delaminate due to erosion in the wind-stream. The very low stiffness of plastics is a big disadvantage but buckling is usually eliminated by proper design. Fiberglas laminates appear usable for practically all structural elements of a guided missile including the tailpipe if appropriate ceramic or metallic liners are used. The overwhelming advantage of plastic structures is the reduced fabricating costs due to less space being required for processing and the feasibility of using semi-skilled labor.

Much current research in this field is devoted to the development of reinforced, low pressure laminates, and their use in both secondary and primary structures should be greatly expanded.

Properties of Applicable Materials

Tabular information for conventional materials is included in Table 14.3-2 to permit easy comparison for preliminary design of structural elements of guided missiles. As is always good practice, final design allowables should be based on exact information obtained from the material manufacturers.

Titanium

Titanium is the newest material available for use in structural design as a possible replacement for both aluminum and stainless steel alloys for elevated temperature, high

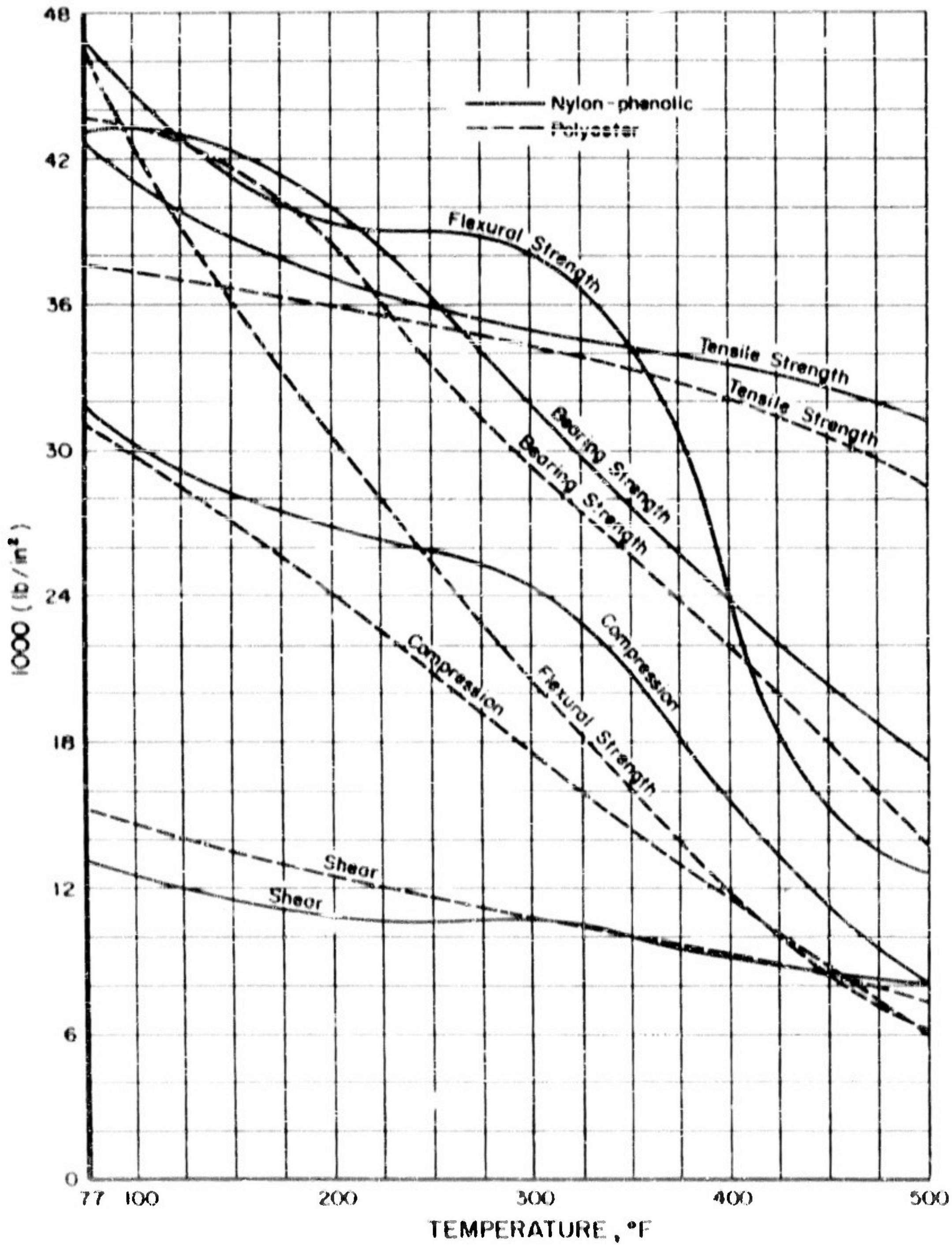


Fig. 14.3-8 AVERAGE STRENGTHS OF PLASTIC LAMINATES AT VARIOUS TEMPERATURES

Glass cloth impregnated with two resins is indicated.

TABLE 14.3-2(a) Condensed Tabulation of Mechanical Properties

Commercial Designation	Form	Condition	Tensile Strength (lb/in^2)	Yield Strength 0.2 per cent offset (lb/in^2)	Elongation (per cent in 2 inches)	Hardness (Brinell)	Reference or Miscellaneous Information
Alloy Steels							
SAE-4130	Sheet, plate, tube, bar and rod	N of MIL specifications t < 0.188 inch	95,000	75,000	25.5	197	Elongation and hardness is for 1-inch rod
SAE-4130	Plate and bar	Annealed t < 1.50 inch	65,000	45,000	28.2	156	Elongation and hardness is for 1-inch rod
SAE-4130	Sheet, plate, tube and rod	Heat treated	150,000	135,000	16	306	
18-8	Sheet and strip	Annealed	75,000	30,000			
18-8	Sheet and strip	Cold rolled 1/2 hard	150,000	110,000			
18-8	Sheet and strip	Cold rolled and heat treated, 1/2 hard	150,000	120,000			
18-8 Type 304	-	Annealed	85,000	30,000	55–63	160	
18-8 Type 304	-	Cold rolled	185,000	160,000	8	400	Sample sheet
18-8 Type 316	-	Annealed	90/100,000	35/45,000	50–60	170/200	
Inconel X	(Gauges 0.025 inch to 0.250 inch) (sheet and strip)	Annealed	100/140,000	40/50,000	35–50	146/241	
Inconel X	(Gauges 0.025 inch to 0.250 inch) (sheet and strip)	Annealed and aged	150/175,000	100/130,000	20–30	293/372	

TABLE 14.3-2(a) continued

Commercial Designation	Form	Condition	Tensile Strength (lb/in^2)	Yield Strength 0.2 per cent offset (lb/in^2)	Elongation (per cent in 2 inches)	Hardness (Brinell)	Reference or Miscellaneous Information
Inconel X	-	Annealed	120,000	55,000	50	175	Sample sheet
Inconel X	-	Hot rolled	188,000	130,000	23	355	Sample sheet
			Aluminum Alloys				
24S-T3	Sheet and plate	Heat treated < 0.250 inch	65,000	48,000	15	-	
24S-T4	Rolled bar, rod and shapes	Heat treated ≤ 3.000 inch	62,000	40,000	16	-	
24S-T3	Tubing	Heat treated	64,000	42,000	12	-	
24S-T81	Tubing	Heat treated, cold worked and aged	68,000	50,000	-	-	
24S-T4	Extruded shapes	Heat treated < 0.250 inch	57,000	42,000	12	-	
24S-T81	Extruded shapes	Heat treated, cold worked and aged	64,000	56,000	-	-	
24S-T36	Sheet	Wrought	72,000	57,000	14	130	
24S-T36	Alclad	Heat treated and rolled	67,000	53,000	11	-	
24S-T86	Alclad	Artifically aged	70,000	66,000	6	-	
24S-T4		Test material	70,800	79,300	-	-	
75S-T6	Sheet and plate	Heat treated and aged 0.040 - 0.249	77,000	67,000	8	-	

TABLE 14.3-2(a) concluded

Commercial Designation	Form	Condition	Tensile Strength (lb/in^2)	Yield Strength 0.2 per cent offset (lb/in^2)	Elongation (per cent in 2 inches)	Hardness (Brinell)	Reference or Miscellaneous Information
75S-T6	Rolled bar, rod and shapes	Heat treated and aged ≤ 3.000 inch	77,000	66,000	7	-	
75S-T6	Extruded bar rod and shapes	Heat treated and aged up to 0.249 inch	78,000	70,000	7	-	
75S-T6	Hand forged stock	Cross section area (in^2) ≤ 16	75,000	64,000	9	-	
75S-T6	Die forgings	Thickness ≤ 4 inches	75,000	65,000	10	135	
75S-T6	Sheet	Wrought	82,000	72,000	11	150	
75S-T6	-	Test material	90,500	79,300	-	-	
			Magnesium Alloys				
FS-1	Sheet	H 24	42/39,000	32/29,000	16-4	73	Dow design. Compression yield 27/25,000 lb/in^2
FS-1	Sheet	O	37/32,000	22/18,500	21-12	56	Compression yield 16/12,000
FS-1	Sheet	F	37/32,000	22/18,000	21-12	-	
O-1	Extrusion	T 5	52/48,000	36/30,000	5-4	82	Compression yield strength 24,000 lb/in^2
ZK 60A	Extrusion	F	45/42,000	38/31,000	12-5	75	
M	Sheet	-	37/32,000	29/22,000	8-4	56	

TABLE 14.3-2(b)

Typical Properties of Cloth Base Polyester Laminates

Cloth	Tensile Strength (lb/in^2)	Compressive Strength (lb/in^2)	Shear Strength (lb/in^2)	Flexural Strength (lb/in^2)
(A) Square woven 0.003 inch t; 2 oz/sq yd	40,400	36,200	18,500	57,100
(B) Square woven 0.007 inch t; 6 oz/sq yd	40,600	25,300	19,300	53,200
(C) Square woven 0.015 t; 12 oz/sq yd	35,400	15,400	18,100	41,100
(D) Unidorectional fabric 0.009 inch t; 9 oz/sq yd				
(parallel)	84,600	47,100	26,800	107,400
(cross)	47,800	39,800	20,300	58,800
(E) Long shaft satin weave 0.009 inch t; 9 oz/sq yd	36,800	35,900	18,600	61,200
(F) Long shaft satin weave 0.013 t; 12 oz/sq yd	49,400	26,900	19,000	57,900

TABLE 14.3-2(c)

Type of Plastic	Direction[1]	Tensile Strength (lb/in^2)	Compressive Strength (lb/in^2)	Shear Strength (lb/in^2)
Thermosetting Plastics				
Grade L phenolic laminate	Longitudinal Transverse	17,000 12,300	25,800 24,700	12,600 13,600
Grade C phenolic laminate	Longitudinal Transverse	14,700 9,900	27,800 27,500	13,000 14,000
Grade XX phenolic laminate	Longitudinal Transverse	16,100 13,700	23,800 23,400	12,300 13,800
High-strength paper phenolic laminate	Longitudinal Longitudinal	25,000 25,000	22,400 22,400	11,990[2] 15,200[3]
Phenolic laminate, glass- and cotton-fabric-filled	Longitudinal Transverse	38,000 37,700	27,000 24,000	18,000 18,600
Resin-impregnated compressed maple	Longitudinal	30,000	20,000	8,800
Lignin laminate	Longitudinal	11,700	17,300	8,700
Cast phenolic	...	10,000	23,600	9,200
Aniline-formaldehyde resin Plasticized Unplasticized		 7,000 9,400	 21,900 22,300	 8,300 9,400
Allyl-type resin Unfilled	 Longitudinal	 4,300	 15,100	 4,000
Kraft paper	Longitudinal	13,000	11,700	9,800
[illegible] paper	Longitudinal	9,900	11,100	8,600
Duck base	Longitudinal	7,000	13,000	8,200
Muslin base	Longitudinal	7,700	10,900	8,500
Urea-formaldehyde fabric-base laminate	Longitudinal Transverse	4,800 5,000	... ...	7,000 7,900
Thermoplastic Plastics				
Cellulose acetate, transparent	...	5,900	7,300	5,800
Cellulose acetate H3	...	6,400	5,800	5,700
Cellulose acetate H5	...	7,400	9,700	8,300
Cellulose acetate butyrate H1	...	4,900	4,500	3,700
Cellulose acetate butyrate H5	...	6,500	6,500	4,900
Polymethyl methacrylate	...	8,600	12,100	8,200
Polyvinyl chloride acetate	...	9,600	12,400	10,000
Polystyrene	...	3,700	15,200	6,100

[1] Direction of shear plane and direction of loading for tension and compression.

[2] Flatwise.

[3] Edgewise.

"Shear Strength of Plastic Materials" Modern Plastics by R. T. Schwartz and K. Dugger, March 1944.

strength-weight ratio applications. It is a light-weight, strong, corrosion-resistant metal which, for structural work at temperatures less than 900°F, approximately fits between steel and aluminum from consideration of density, modulus, and strength. For example, where titamium can be substituted, only 60 per cent as much weight is required for stainless steel, section for section. The main advantages of titanium as a structural material are:

1. Up to approximately 700°F, it has a higher strength-weight ratio than any other structural material,
2. it is virtually non-corrosive and non-erosive (much better than stainless steel or monel) in salt air, and
3. fabrication can be done with standard processes and machinery (but with some changes in tools, feeds, and speeds).

Disadvantages are:

1. High cost of raw material,
2. difficulty in rapidly processing high strength alloys,
3. difficulty in making ductile welds, and
4. inconsistency of physical properties.

Nominal mechanical properties and chemical composition are given in Table 14.3-3 and Table 14.3-4. Titanium melts at temperatures between 2550° and 3150°F, depending on the alloying constituents; its density varies from 0.16 to 0.17 lb/in^3 and hardness from 190 to 270 Brinell Hardness Number. Surface hardness comparable to nitrided steel is readily obtainable by appropriate heat treatment. The modulus of elasticity is about 16×10^6 lb/in^2 (approximately half that of steel) and drops to about 12×10^6 at 800°F (Fig. 14.2-4). Apparently cold-working changes the value of the modulus to a degree not usually encountered in

TABLE 14.3-3 Nominal Mechanical Properties for Titanium and Titanium Alloys

Commercial Designation*	Form	Condition	Yield Strength 0.2 per cent offset (lb/in^2)	Tensile Strength (lb/in^2)	Elongation (per cent in 2 inches)	Reduction of Area (per cent)	Hardness: Rockwell	Hardness: Brinell
Commercial Titanium								
Ti-55 A	Sheet and strip	Annealed	48,000	65,000	26.5	...	R_B80	...
Ti-75 A	Sheet and Strip	Annealed	75,000	84,000	21	...	R_B90	...
	Plate	Annealed	68,000	85,000	21.5	...	...	219
	Wire	Annealed	72,000	83,000	22.5**	47.5	...	...
		Cold drawn, full hard	125,000	145,000	11.5**	37.5	...	...
	Forgings, hot-rolled bars	Annealed	50,000	80,000	25**	...	...	190
RC-55	Sheet, bar, plate	Annealed	65,000	75,000	25	55	R_A50-54	...
	Forgings	Annealed	65,000	75,000	15	30	R_A50-54	...
MST Grade III	Sheet	Annealed	72,000	80,000	25	55	R_A60	...
		Cold worked, 50 per cent	110,000	125,000	12	30	R_A64	...
	Forgings	As forged	72,000	80,000	25	55	R_A62	...
RC-70	Sheet	Annealed	80,000	90,000	20	50	R_A54-58	...
		1/2 hard	105,000	120,000	12	35	...	...
	Forgings	As forged	80,000	90,000	15	30	R_A54-58	...
MST Grade IV	Sheet, 0.040 inch	Annealed 1 hour at 1300°F	85,000	100,000	18	15	R_A61	...
		Cold worked, 37 per cent	120,000	130,000	6	14	R_A65	...
	Forgings	Hot forged, 80 per cent reduction	75,000	80,000	18	50	R_A61	...
Ti-100 A	Sheet and strip	Annealed	95,000	110,000	17.5	...	R_A56	...
	Plate	Annealed	100,000	110,000	18.5	...	...	270
	Wire	Annealed	88,000	100,000	22.5**	47.5	...	...
		Cold drawn, full hard	160,000	190,000	13.5**	25	...	...
	Forgings, hot-rolled bars	Annealed	98,000	102,000	20**	...	...	253
Titanium Alloys								
MST 3 Al-2 Fe	Sheet, 0.040 inch	Annealed 1 hour at 1300°F	...	140,000	14	...	R_A68	...
		Cold worked, 37 per cent	...	180,000	6	...	R_A70	...
	Forgings	Hot forged, 90 per cent	135,000	145,000	12	30	R_A68	...
RC 130 B	Bar	Annealed	140,000	150,000	20	40	...	...
	Forgings	As forged	130,000	150,000	15	30	R_C33-36	...
MST 3 Al-5 Cr	Forgings	Hot forged, 90 per cent reduction	152,000	165,000	8	25	R_A71	...
		Furnace cooled		165,000	10	...	R_A73	...
Ti-150 A	Plate	Annealed	120,000 min	152,000	12 min	...	...	341
	Forgings, hot-rolled bars	Annealed	120,000 min	150,000	15 min	...	...	341
Ti-175 A	Plate	Annealed	140,000 min	172,000	8 min	...	...	379
	Forgings, hot-rolled bars	Annealed	140,000 min	170,000	10 min	...	...	379
Ti-150 B	Sheet and strip	Annealed	135,000 min	160,000	10	...	R_C35	...
	Plate	Annealed	135,000 min	160,000	10	...	...	322
MST 2.5 Fe-2.5 V	Sheet, 0.040 inch	Annealed 1 hour at 1300°F	125,000	135,000	10	...	R_A65	...
		Cold worked, 37 per cent	170,000	175,000	2	...	R_A68	...
	Forgings	Hot forged, 90 per cent reduction	100,000	130,000	12	35	R_A65	...
RC-130 A	Sheet	Annealed	130,000	150,000	25	35	R_C33-36	...

*See composition table (Table 14.3-4).

**Per cent elongation in 4 diameters.

TABLE 14.3-4 Composition of Commercial Titanium and Titanium Alloys

Designation	Producer	Nominal Composition (per cent) C	O	N	Al	Cr	Fe	Mn	V	Mo	H
Commercial Titanium											
Ti-55 A	Titanium Metals	0.02 max	Trace	0.02	..	..	0.10	..	..	..	0.02 max
Ti-75 A	Titanium Metals	0.02 max	Trace	0.02	..	..	0.10	..	..	..	0.02 max
RC-55	Rem-Cru	0.2 max	(a)	(a)	..	..	(a)	..	..	..	..
MST Grade III	Mallory-Sharon	0.25 max	..	..	..	..	..	..	..	..	..
RC-70	Rem-Cru	0.2 max	(a)	(a)	..	..	(a)	..	..	..	..
MST Grade IV	Mallory-Sharon	0.3–0.8	..	..	..	..	..	..	..	..	..
Ti-100 A	Titanium Metals	0.02 max	Trace	Trace	..	..	0.1	..	..	..	0.02 max
Titanium Alloys											
Aluminum-iron alloy MST 2 Al-2 Fe	Mallory Sharon	0.5	..	..	2	..	2	..	..	..	..
Aluminum manganese alloy RC-130 B	Rem-Cru	0.2 max	(a)	(a)	4	..	(a)	4	..	..	..
Chromium-aluminum alloy MST 3 Al-5 Cr	Mallory-Sharon	0.5	..	..	3	5	..	..	..	..	..
Chromium-iron alloys											
Ti-150 A	Titanium Metals	0.02	0.25	0.02	..	2.7	1.3	..	..	..	0.02 max
Ti-175 A	Titanium Metals	0.02	0.5	0.04	..	3.0	1.5	..	..	..	0.02 max
Chromium-iron-molybdenum alloy											
Ti-150 B	Titanium Metals	0.02 max	Trace	0.02	..	5	5	..	..	5	0.02 max
Iron-vanadium alloy MST 2.5 Fe-2.5 V	Mallory-Sharon	0.5	..	..	..	..	2.5	..	2.5	..	..
Manganese alloy RC-130 A	Rem-Cru	0.2 max	(a)	(a)	..	..	(a)	7	..	..	..

(a) Few hundredths to few tenths.

NOTE: The Mallory-Sharon Titanium Corp. has changed the designations of its alloys as follows:

Old	New
L 2851	MST Grade III
L 2749	MST Grade IV
L 2748	MST 3 Al-5 Cr
L 2841	MST 2.5 Fe-2.5 V
L 2852	MST 2 Al-2 Fe

other engineering materials and this, in part, accounts for the variation of 5 to 15 per cent (depending on the temperature) in the experimental values. The endurance limit of titanium is very good with values generally exceeding 50 per cent of the tensile strength, and preliminary information on impact properties indicates a very high impact resistance over the temperature range of 0° to $600\text{-}800^{\circ}F$. Considerable scatter of the data gives evidence of variation in the material as received from the mill but, on the whole, titanium shows no severe notch sensitivity and does show a gradual rather than an abrupt change from ductile to brittle fracture as a function of temperature.

Commercially pure titanium and alloys respond to cold-work, although generally it is preferable to achieve strength by alloying rather than by work-hardening because of the attendant loss in ductility. For guided-missile components where exposure to the higher temperatures is for very short periods, design allowables can be based on work-hardened values.

Currently, commercial titanium and titanium alloys can be obtained in the forms shown in Table 14.3-5. The variety is adequate for preliminary design, but the manufacturers should be consulted for additional information.

Forging of titanium and its alloys may be accomplished by conventional procedures, but more force and heavier dies are usually required. A sheet can be formed by bending, spinning, drawing, cupping, stretch forming, and extruding. The metal is most easily worked at elevated temperatures ($500\text{-}1200^{\circ}F$) but for most operations room temperature and techniques applicable to working stainless steel usually suffice. Anodizing improves wire drawing and may improve some of the other forming operations.

Titanium may be machined by using much the same methods usually applied to stainless steels. The material is springy and tough even in the annealed state and, because of the tendency to work-harden, requires sharp tools, heavy machines, and heavy positive feeds for cutting operations.

TABLE 14.3-5 Available Forms of Titanium and Titanium Alloys

Designation	Sheet	Strip	Plate	Wire	Bars	Rod	Forging Billets	Forgings	Welded Tubing
Commercial Titanium									
Ti-75 A	x	x	x	x	x	x	x	x	x
Titanium Alloys*									
MST 2 Al-2 Fe	x	x			x		x	x	
RC-130 B		x		x	x		x	x	
MST 3 Al-5 Cr					x		x	x	
Ti-150 A			x	x	x		x	x	
Ti-175 A			x		x		x	x	
Ti-150 B	x	x	x	x					
MST 2.5 Fe-2.5 V	x	x			x		x	x	
RC-130 A	x								

*See composition table.

Titanium can be welded with ease, but its affinity for oxygen, nitrogen, and hydrogen requires shielded arc welding. Sheet stock may be spot and seam-welded and even flash-butt welding has been used. Welding techniques have been receiving considerable attention recently and new developments will improve application of most processes. Brazing and soldering techniques have not yet been developed, but appear feasible. Casting of titanium has been accomplished on a commercial basis, and permanent mold casting of small parts has been successful. Additional development is required to permit the casting of large sizes.

Molybdenum

Molybdenum with its unique combination of outstanding high-temperature properties and availability is one of the most promising metals for use at temperatures above 1600^{O}F, and if above 3000^{O}F stresses are not excessive. As a heat-resistant material, molybdenum could be employed as a pure metal or as a major constituent of an alloy. Molybdenum cannot be melted and cast by conventional means, but chemically-prepared powder can be consolidated into ingots suitable for working into usable forms by either powder metallurgy or arc-casting techniques. Since ingot sizes up to 1000 lbs have been produced, it appears that size is no longer a major limitation to the use of molybdenum as an engineering material. The melting point of molybdenum is very high, 4750^{O}F, which is exceeded only by tungsten and tantalum. Its density is 0.368 lb/in^{3}; its specific heat and coefficient of thermal expansion are about half that of steel (e.g., 3.0 x 10^{6} in/in/^{O}F at 70^{O}F); and its thermal conductivity is three to five times greater (e.g., 0.28 Btu/ft^{2}/sec/^{O}F/in). These characteristics provide molybdenum with

advantageous heat-transfer and thermal-shock properties, especially useful where non-uniform temperature conditions and temperature-cycling effects are involved. Dimensional stability is consequently greater and thermal stress problems are reduced.

Molybdenum also has a high modulus of elasticity, making it favorable for applications where rigidity requirements prevail. This modulus is not seriously affected by elevated temperatures (see Fig. 14.2-4), but does vary somewhat with grain direction and cold-work. Considerable variation exists in the published data on strength properties of molybdenum (typical values are given in Fig. 14.2-1, Table 14.3-6, and Table 14.3-7), and it is clear that the mechanical properties vary with impurities in the basic metal and also with the fabrication history.

The room-temperature ductility of molybdenum is relatively good, increasing with temperature. In the present stage of development it cannot be considered as a ductile metal suitable for comprehensive structural usage. Molybdenum appears to be very brittle under many conditions and is quite "strain-rate" and "notch" sensitive. Tests indicate a sharp decrease in impact strength occurs below room temperature. Appropriate consideration must therefore be taken when designing for impact loads which occur during winter transportation. The creep and rupture strength of molybdenum is high, compared to other pure metals used in high-temperature alloys, and it is superior to conventional alloys used above 1600°F.

The major problem to be overcome in the application of molybdenum as a heat-resistant metal is the rapidity of surface oxidation. At 1800°F, for example, in slow-flowing air, molybdenum oxidizes at the rate of 0.02 to 0.05 inch of thickness per hour. Various methods of providing adequate surface protection are being investigated, and some are moderately successful.

TABLE 14.3-6 Tensile Properties of Molybdenum at Elevated Temperatures

Testing Temperature (°F)	Condition	Tensile Strength (lb/in^2)	Yield Strength 0.2 per cent	Proportional Limit	Elongation (per cent in 2 inches)	Reduction in Area (per cent)
(arc-cast, hot rolled to 1/2-inch-diameter bars)						
80	As rolled	95,140	-	-	3	2
	Stress relieved	91,000	84,850	-	10	9
	Recrystallized	67,500	63,500	-	46	36
1600	As rolled	61,400	50,100	26,000	18	72
	Stress relieved	50,600	44,500	21,500	22	81
	Recrystallized	34,400	11,600	3,500	46	84
1800	As rolled	49,900	40,500	23,000	19	81
	Stress relieved	40,500	35,600	22,500	32	81
	Recrystallized	29,000	10,500	5,700	49	75
1950	As rolled	38,000	31,600	24,000	29	83
	Stress relieved	31,400	22,800	16,500	36	84
	Recrystallized	21,500	8,550	4,100	35	52

NOTE: The test bars were sprayed with aluminum to prevent oxidation while testing at elevated temperatures. Except where noted, the test bars were brought to temperature with the furnace and held for 20 minutes before testing. They were loaded at the rate of 1000 lb/in^2/min. The hot-rolled material had been annealed at 1800°F for 20 minutes and then machine straightened while warm. The best stress relieving temperature, on the basis of combined tensile strength and ductility, was 1850°F. A satisfactory temperature to recrystallize the as-rolled material was 2250°F.

TABLE 14.3-7 Directional Properties and Effect of Annealing Temperature on Cold Rolled Molybdenum Sheet at Room Temperature

Property	Vitreous Ceramics, Fine Texture: Steatite MgO SiO_2	Vitreous Ceramics, Fine Texture: Zircon ZrO_2 SiO_2	Vitreous Ceramics, Fine Texture: Alumina Al_2O_3	Made from Natural Stone: Aluminum Silicate	Refractories, Medium Grain: Cordierite MgO SiO_2 Al_2O_3	Refractories, Fine Texture: Zircon ZrO_2 SiO_2	Refractories, Granular: Zirconium Oxide ZrO_2
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Water absorption (per cent)	0 to 0.02? Impervious	0 to 0.02? Impervious	0 to 0.02? Impervious	1 to 3 Technically vitreous	10 to 15 Highly porous	8 to 14 Highly porous	12 to 16 Highly porous
Specific gravity	2.6?	3.7	3.9?	2.3?	2.1?	2.9?	2.8?
Density	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Standard body colors	White	White	Blue?	Pink?	-	White	Orange
Softening temperature (°F)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Safe temperature at continuous heat (°F)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Hardness (Mohs' scale)	7.5?	8	9?	8?	7?	-	-
Thermal expansion linear coefficient (in/in/°F 70-1200°F)	[illegible] $\times 10^{-6}$	2.3 $\times 10^{-6}$?	2.8 $\times 10^{-6}$?	[illegible] $\times 10^{-6}$	1.8 $\times 10^{-6}$?	2.8 $\times 10^{-6}$?	[illegible] $\times 10^{-6}$
Tensile strength (lb/in^2)	[illegible]	[illegible]	-	[illegible]	[illegible]	-	-
Compressive strength (lb/in^2)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Flexural strength (lb/in^2)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Resistance to impact (1/2-inch rod) (in-lb)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Thermal conductivity (Btu/sq-ft/hr/°F/in)	[illegible] $\times 10^{-4}$	[illegible] $\times 10^{-4}$	[illegible] $\times 10^{-4}$	[illegible] $\times 10^{-4}$	[illegible] $\times 10^{-4}$	[illegible] $\times 10^{-4}$	[illegible] $\times 10^{-4}$

Materials shown have been grouped according to vitrification. [illegible]

Impervious - 0 to 0.02 per cent
Vitrified - [illegible] per cent
Technically vitreous - [illegible] per cent
Semivitreous - [illegible] per cent
Highly porous - above [illegible] per cent

[illegible]

Most of the processes can be classified under the general types of either "diffusion" coatings or ceramic coatings [46,48]. The former are typified by a surface covering (applied by electroplating, vapor phase deposition, or cladding) with a metal that has better resistance to oxidation than molybdenum or one that forms an oxidation resistant alloy with it. These coatings usually fail because of the diffusion of the molybdenum into the protective layer. Life of over 5000 hours at 1800°F, and over 300 hours at 3100°F has been reported with coatings of molybdenum disilicide 2 mils thick. The coatings have also shown good service under load and when subjected to thermal cycling, and are useful up to 3300°F, the melting temperature.

Some ceramic coatings have also shown promise. Coatings developed by the Bureau of Standards show no deterioration when exposed in air at 1650°F for 70 hours. Both diffusion and ceramic coatings provide adequate protection for usage not involving severe shock or impact loading.

The development of oxidation-resistant alloys is also being investigated, although this approach does not appear to offer much promise. The amounts of alloying additions required to provide adequate protection are sufficient to make the alloys completely unworkable.

Most procedures for forming molybdenum are conventional. As a result of the high transition temperature, forming operations such as shearing, bending, crimping, drawing, upsetting, and spinning should be performed at elevated temperatures to minimize the occurrence of brittle cracks. Many forming operations on molybdenum cause cracks when carried out at room temperature, but it can be readily worked at temperatures of about 400°F. However, sheet can be cold-rolled to a thickness of 0.001 inch at room temperature, but for cross-rolled molybdenum sheet between 0.020 and 0.040 inch sheet thickness, working

should take place within the temperature range of 200° to $325^{\circ}F$; for heavier stock, 900° to $1000^{\circ}F$ temperatures should be employed. Molybdenum can be spun by the customary procedures at temperatures from 200° to $400^{\circ}F$. Cross-rolled sheet usually is specified for drawing, spinning, and forming operations to insure that the sheet has sufficient ductility for forming in all directions. In machinability, molybdenum more nearly resembles SAE 1040 steel heat-treated to Rockwell C30 than any other material.

Molybdenum parts are generally joined by riveting with molybdenum rivets or by brazing with copper or silver solders. For high-temperature applications, tantalum foil has been employed as a brazing material, the operation being performed under water to prevent oxidation of the tantalum [46]. A nickel-chromium alloy containing 2 to 3 per cent boron (Wall-Colmony No. 6) has been reported to be a good brazing alloy for service up to $2000^{\circ}F$. Resistance or arc welding techniques have been successful, but the weldment is usually brittle and reinforcement is required for parts to be formed after welding. Spot or seam welding can be used.

Materials for Fuel Cells

The selection of materials suitable for use as fuel cells require consideration of several factors.

1. The tensile strength must be great enough to withstand the dynamic movement of the fuel within the tank,
2. it must be impervious to hydrocarbons for long periods of time to permit fueled stowage as well as factory tests without subsequent flushing,

3. it must be extremely flexible to permit easy installation and reliable operation,
4. it must have a high degree of wearability (or abrasion) and tear resistance to permit cycling for test purposes without potential rupture when subjected to flight loads and dynamics,
5. it must be light in weight and small in volume, and
6. it must have adequate high temperature resistance since parts of the cell can be in intimate contact with the tank walls. The cooling effect of the fuel itself helps to ameliorate this problem, however.

Typical tests made to select a fuel cell for an antiaircraft missile are shown in Table 14.3-8. As a result of these tests, a cell made of neoprene coated (4 oz/yd^2) nylon fabric has been developed. This cell is adequate for use between temperatures of -40° and 500°F; although the melting point of nylon is 480°F, the neoprene coating increases the allowable operating temperature. The cell withstands repeated cycling without damage to either the fabric or the seams.

Plastic cells fabricated from Teflon or Kel-F are very good, but fabrication of unusual shapes is difficult due to the difficulty of making reliable joints. With simple geometrical configurations and closures by means of mechanical means such as clamps or sealing rings, very satisfactory fuel cells can be made from plastics of this type.

TABLE 14 3-8 Typical Tests Made to Select a Fuel Cell for an Antiaircraft Missile

Composition	Test Results	
	Temperature	Physical
(A) Neoprene-coated No. 116 glass cloth of 0.004-inch gauge. Plain lap seams. Spread-neoprene coating.	Probably suitable up to 500°F.	Cell cracked during installation. Not recommended for as much as a single flight. Seams did not stand flexing.
(B) Neoprene-coated No. 128 glass cloth of 0.007-inch gauge. Spread-neoprene coating. Improved seams.	Probably suitable up to 500°F.	Recommended for use only where limited testing is required. Glass cloth cannot take repeated flexing.
(C) US538N standard aircraft cell construction with 0.009-inch gauge. Nylon fabric style A2634.	50 per cent reduction in strength when exposed to 370°F hot plate test for 3 minutes.	Propylene oxide caused undue swelling of the Buna-N constituent. When used with kerosene, the cells were successfully tested for many cycles.

Silicone, thiokol, and GR-S were eliminated as possible materials because of failure to meet either temperature or fuel resistance requirements.

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